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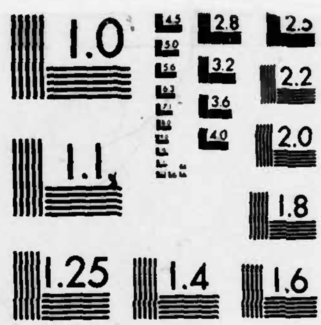

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USAF MOBILE POWER AND FACILITY ELECTRICITY POWER SYSTEMS ANALYSIS

Volume I - Technical Report

APPLIED CONCEPTS CORPORATION
109K NORTH MAIN STREET
WOODSTOCK, VIRGINIA 22664

MARCH 1984

FINAL REPORT FOR PERIOD JANUARY 1982 - SEPTEMBER 1983

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This report has been reviewed by the Office of Public Affairs (ASD/PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Valerie J. Van Griethuysen

VALERIE J. VAN GRIETHUYSEN
Project Engineer
Energy Conversion Branch

Paul R. Bertheaud

PAUL R. BERTHEAUD
Chief, Energy Conversion Branch
Aerospace Power Division
Aero Propulsion Laboratory

FOR THE COMMANDER

J. D. Reams

JAMES D. REAMS
Chief, Aerospace Power Division
Aero Propulsion Laboratory

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This research built upon previous work which developed a data base for advanced terrestrial energy systems (ATES), and a computerized methodology for multiple criteria decision making (MCDM). Research determined the electric power (MEP) and facilities energy generating system (FEGS) needs. Advanced technologies have little potential to enhance FEGS operational effectiveness, but offer cost savings, especially for remote site and self sufficiency missions. MEP mission support can be enhanced by free piston systems in small sizes, by kinematic stirling and phosphoric acid fuel cells in mid sized applications (flightline, communications support) and by regenerative gas turbines in large systems. R&D programs are recommended to achieve the enhanced operational and cost potential.

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FOREWORD

This final report presents the results of research completed for the Energy Conversion Branch (POO), Aerospace Power Division (PO), Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories (AFWAL), Wright-Patterson AFB, Ohio 45433, under contract number F33615-81-C-2077, "Mobile Power Systems Analysis."

The work reported herein was performed during the period 4 January 1982 to 30 September 1983, under the direction of the Project Engineer, Ms. Valerie Van Griethuysen.

The Project Director and principal author of this final report was Mr. J. Scott Hauger. Major contributors to research were Mr. William H. Adams and Mr. James A. Simpson. Mr. Robert L. Uphoff was responsible for computerized systems analysis support, including the design and production of the Multiple Attribute Decision Model (MADM) which was used in the major analytical task. A detailed description of this technology assessment tool is available in "User's Manual for the Multiple Attribute Decision Model (MADM)," dated June 24, 1983.

The research reported herein builds upon the work accomplshed by the Institute of Gas Technology, 3424 S. State Street, Chicago, IL 60616, as performed under USAF contract F33615-80-C-2041, and as reported in AFWAL-TR-82-2019, "USAF Advanced Terrestrial Energy Study, Final Report: September 1980 - February 1982." It also builds upon the results of work accomplished by the University of Dayton School of Engineering, Dayton Ohio 45469, as performed under contract F33615-77-C-2059, and as reported in AFWAL-TR-81-2112, "Advanced Technology Multiple Criteria Decision Model, Final Report: 1 June 1980 - 30 November 1981."

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EXECUTIVE SUMMARY

I. Background and Statement of Work

The objective of this research was to determine the potential of advanced electrical power systems to satisfy future USAF electrical power needs for mobile electric power systems (MEPS) and facilities electrical generating systems (FEGS).

The research built upon two previous projects sponsored by Air Force Wright Aeronautical Laboratories, Power Conversion Branch (AFWAL/POOC). The USAF Advanced Terrestrial Energy Study (ATES) provided a detailed statistical characterization of seventeen advanced power technologies across a spectrum of sizes (5-5,000 kW), and over time (1980-2000). The Multiple Criteria Decision Model (MCDM) is a computer model developed by the University of Dayton School of Engineering to compare alternatives with multiple attributes, using multiple criteria. These products of previous research provided an important analytical tool for a comparison of USAF applications to technologies' potential.

Research was initiated by AFWAL for consideration of USAF mobile electric power (MEP) support missions. As this research was nearing completion, USAF Engineering and Services Center (ESC) provided additional funds for consideration of facilities electric applications. The statement of work, in its final form, consisted of six tasks:

1) Determine USAF mission requirements (future needs) for MEP systems.

2) Test and improve MCDM for conducting the analysis.

3) Assess advanced technologies' potential to meet MEP requirements.

4) Determine system deficiencies where R&D can result in useful systems for USAF MEP applications.

5) Estimate R&D program costs to achieve new technologies' potential.

6) Conduct an analysis for FEGS applications.

II. The Progress of the Research

An important part of this research was time spent in the field with MEP and FEGS systems users. Through a process of interviews and survey, the research team constructed a unique data base on USAF mission requirements for electrical support equipment. Interviews were held at twelve MEP using units, two Air Logistics Centers, three AFSC supporting offices, and six headquarters' logistics and maintenance staffs for MEP applications. Seven bases civil engineering staffs were interviewed as well as headquarters' staffs at ESC and HQ USAF to gather information regarding facilities' applications. The research team received 276 survey responses from MEP users, and 49 responses to a more limited FEGS survey.

Meanwhile, three technical subcontractors were validating and updating the ATES data base on technologies. The technologies considered and the responsible technical subcontractors were:

Technology	Subcontractor
Free piston Stirling engines Kinematic Stirling engines	MTI, Inc., Latham, NY (Stirling Engine Systems Div.)
Non-regenerative gas turbines Regenerative gas turbines Closed cycle gas turbines	MTI, Inc., Latham, NY (Research & Development Div.)
Phosphoric acid fuel cells Solid Polymer fuel cells	Giner, Inc., Waltham, MA
Turbocharged diesel engines Turbocompound diesel engines Adiabatic diesel engines	Mr. Gregory Flynn, St. Clair Shores, MI

For FEGS applications, three varieties of stand alone solar photovoltaic technologies and two wind turbine technologies were also considered. Data for these technologies was taken from the ATES without further validation or update.

During the course of research, the research team evolved the MCDM model into a microcomputer-based, user friendly program which is now available for other technology assessment applications. The improved model, christened MADM for Multiple Attribute Decision Model, corrected several problems revealed during testing of the MCDM version. MADM is available on diskette for use on the Apple II family of computers. A full report is available as the User's Manual for the Multiple Attribute Decision Model (MADM).

Using MADM and a simple life cycle cost comparison, the research team compared the advanced technologies and baseline systems for their operational and cost effectiveness in USAF mission support applications. The application scenarios were selected to reflect the major USAF uses of electrical generating systems. Projections were made for 1985, 1990, and 2000. The applications studied were:

1) For MEP applications:

- Flightline Power Support (60 kW)
- TACS Power Support (5 kW and 10 kW)
- Other/Future Tactical Precise Power (100 kW)
- BARE BASE/Rapid Deployment Support (750 kW)
- Utility Power (5 kW - 250 kW)

2) For FEGS applications:

- Emergency/Backup Power Generation (5 kW-5,000 kW)
- Remote Site Power Generation (5 kW-5,000 kW)
- Base Self Sufficiency (750 kW and 5,000 kW)
- Centralized Aircraft Support (750 kW and 5,000 kW)

The analysis identified promising systems in a variety of MEP applications where significant increases in cost and operational effectiveness can be expected from the development and implementation of advanced technology electrical power systems. For FEGS applications, the advanced technologies are not anticipated to substantially enhance operational capabilities. The potential does exist for significant cost savings in some FEGS senarios.

Detailed projections of cost and operational effectiveness for all technologies in all scenarios in all years are found in appendices to this report. Processed results for comparing the relative cost and operational effectiveness of all systems in all applications for the year 2000 are found in Chapter V for MEP applications and Chapter VIII for FEGS applications.

The technical subcontractors identified and characterized eleven research projects which could lead to effective systems in USAF MEP applications by the year 2000. These projects were structured to overcome deficiencies in the current state of the art, and to result in systems whose operational and cost characteristics equalled or bettered those in the ATES.

As a final, integrative step, the research team analyzed and interpreted the results of these tasks to derive the following findings:

III. Results, Conclusions and Recommendations

A. Mobile Electric Power Systems

1. There exists a positive potential for USAF to realize both cost and operational effectiveness improvements in mobile electric power mission support through the introduction of advanced technology systems in the 1990-2000 time-frame.

2. The highest potential payoff is in areas where electrical generator support is most clearly mission related. These areas are:

a. Small (1-5 kW) generators in support of mobile command and control units (TACPs and MAC CCTs).

b. Medium sized (45 to 100 kW) generators in support of flightline and electronics missions.

c. Large (750 kW) generators in support of BARE BASE and rapid deployment missions.

Utility generators also stand to benefit from advanced technology development, and contribute to the overall cost benefits to be realized.

3. Free piston Stirling engine driven generators have the highest potential to meet small MEP applications. Not only does this technology score highest for projected cost and operational effectiveness, its characteristics of compactness, low weight, fuel efficiency and quiet operation are especially well suited to its most important mission applications.

4. Kinematic Stirling engines and phosphoric acid fuel cells have the highest potential to meet mid-sized flightline and electronics support applications. Increased fuel efficiency and quieter operation are important characteristics of these technologies. Research and development is necessary to realize light weight systems of proven reliability.

5. Regenerative open cycle gas turbines have the highest overall potential to meet USAF requirements for large mobile power plants in support of rapid deployment. Other technologies have higher operational effectiveness potential, but are not cost competitive at low duty cycles.

6. USAF will gain from the implementation of research and development programs in these three areas. The benefits to be derived are enhanced operational effectiveness and cost savings totalling over $250 million, (about $165 million if discounted for risk), over system lifetimes. The following is a synopsis of the R&D opportunity:

Program Area	Program Cost	Duration	Cost Ratio	Payoff ($)	Operational Payoff
Small Free Piston	$ 3.3 M	3 years	18:1	$ 60 M	2.2:1
Mid sized Fuel Cell & Kinematic Stirling	$40 M	10 years	6:1	$171 M	1.6:1
750 kW Regenerative Gas Turbine	$10 M	6 years	2:1	$ 20 M	1.2:1

7. There exists a great potential and a great need to enhance the operational and cost effectiveness of both current and advanced technology MEP systems through enhanced planning and management in the area of integrated logistics support and in duty cycle management.

8. For effective research management, this investigative research should be updated triannually.

B. Facilities Energy Generating Systems

1. The major use for FEGS is in emergency/backup applications. Current technologies are operationally effective in these applications. Advanced technology systems offer only marginal improvements.

2. Current technologies are also operationally effective in remote site applications, however, advanced technology systems offer substantial potential for cost savings. There are several good candidate systems in each size range.

3. Given the lack of potential for notable enhancement of operational effectiveness, the diversity of technologies which can result in enhanced cost effectiveness, and the limited number of USAF remote site applications, no major impetus seems to exist for undertaking an autonomous USAF technologies development program for any of the fuel burning technologies.

4. Facilities applications can benefit from the results of any MEP applications R&D which USAF should choose to undertake. It would be wise and reasonable for facilities engineering programs to contribute to and participate in MEP development programs to encourage and realize technology transfer. The greatest opportunities are in small and large generators, where the potential for cost benefits from advanced technology application currently exist.

5. The most attractive areas for FEGS R&D, where interests differ from MEP needs, are those of natural gas burning systems for base self sufficiency, and adiabatic diesels for remote site applications. The major dynamic for such R&D is not technology driven, however, but depends on policy decisions regarding base self sufficiency, and on civil sector research in electric energy generators.

6. This study did not comprehensively address renewable energy systems for facilities applications. However, two tentative conclusions are possible based upon the ATES data and designs: Stand alone, i.e. non-hybrid, non-grid connected photovoltaic systems do not appear attractive for general facilities applications. Wind turbines appear be generically attractive enough to warrant detailed consideration whenever site specific factors are encouraging.

7. If USAF institutes a base self sufficiency policy which includes a requirement or potential for power generation inside the fence, then advanced technologies have the potential to be operationally effective at a price which is competitive with utility electric costs. The scope and scale of investment and potential cost savings would almost certainly require a major R&D program.

8. There exist major deficiencies in integrated logistics support for facilities electric generating systems. The lack of standardization has had major impacts on training, spare parts availability, and readiness. Further research in this area would almost certainly result, if implemented, in enhanced cost and operational effectiveness.

I. Introduction

A. Program Objective

The overall objective of this program was to determine the potential of advanced electrical power systems to satisfy future USAF electric power needs for mobile electric power systems (MEPS) and for facility electricity generating systems (FEGS).

B. Background

The Mobile Power System Analysis and Facility Electricity Generating System Analysis program was a culmination of research which began in the mid-1970s, subsequent to the Arab oil embargo. Events in the 1970s led to a rapid escalation in fuel prices and to a general concern for the security of fuel supplies, within the Department of Defense (DoD) as in the nation as a whole. In cooperation with the other services and with the newly-formed Department of Energy (DOE), USAF launched a number of programs to promote fuel conservation, to investigate alternative fuels, and to develop alternative sources of energy for USAF mission requirements.

One programmatic thrust undertaken by the USAF research and development community was in the area of alternative power conversion systems for terrestrial applications. The same characteristics of low fuel efficiency and of fossil fuel dependence which were suddenly of high concern for aeropropulsion and automotive applications were also of concern for mobile electric power systems. The principal technologies in use for ground power generation for mobile applications were those of gasoline and diesel engine driven generators, generally as derived from automotive engines. Beginning in the 1960s, gas turbine engine driven generators appeared in certain applications where light weight was considered important. This technology was generally derived from airborne power plants.

Facilities electricity for nearly all Air Force Bases (AFBs) is purchased from the local utility. Emergency and backup power is typically provided by diesel or gasoline driven generators; i.e., the same basic technologies which provide mobile electric power. The challenge presented by the Arab oil embargo served as a stimulus to the general reconsideration of the technology base for USAF electric power systems. This implied an examination of both applications and resources.

One resource was the vast technology development program undertaken by DOE. A surprisingly large number of alternative technologies for the production of electricity came under consideration, as did new ways to improve existing technologies. Some approaches, which had been considered in the nineteenth century, such as Stirling cycle engines, wind turbines, and solar thermal electric plants, were reconsidered for twentieth century development. Some ideas which had been developed for space applications, such as photovoltaics and fuel cells, were investigated for their applicability to terrestrial power plants.

Like the other services, USAF stood to benefit a great deal from the research into energy technologies being sponsored by DOE. However, technology transfer from DOE alone, could not be sufficient to meet USAF needs. This is because of the differences in applications' requirements between USAF and the civil sector. Those differences are of two sorts. First, the USAF combat mission imposes special constraints on system design for survivability, durability and mobility, which are different from civil sector requirements. Second, USAF organization and physical plant structures are not the same as typical civil sector organizations and plants. These facts have definite implications for design for mission and cost effectiveness of electrical generating systems.

Both of the sponsors of this research, the Aero Propulsion Laboratory (APL) and the Engineering and Services Laboratory (ESL), developed their understanding of the need to characterize USAF energy applications and to match requirements against technological opportunities during the period 1975 - 1980. As early as 1976, APL undertook to prepare a definitive technological data base through the Terrestrial Energy Study program. The updated (1982) version of this research, the Advanced Terrestrial Energy Study (ATES) became the principal data base for this research.

Around the same time, APL undertook to develop a computer model which could deal with a massive data base for technologies and compare its descriptive parametric data to USAF applications requirements. The proximate result of this research was the Multiple Criteria Decision Model (MCDM), completed in 1981.

By early 1982, therefore, the basic tools were in place to compare USAF energy requirements to those energy technologies expected to become available during the period 1985 - 2000. The major tasks remaining were three:

1) To gather information regarding the principal USAF applications and requirements for electrical energy systems.

2) To combine requirements information for USAF applications with the technologies' data base, using the model.

3) To analyze the output of the model to determine the potential of advanced electrical power systems to meet USAF needs.

In 1981, APL sought, through a competitive procurement, a contractor to undertake these tasks for the mobile electric power systems which fall within APL's area of responsibility. In January 1982, the contract was awarded to Applied Concepts Corporation. During the course of research, ESL became aware of the applicability of the data base and the model to facilities energy systems. Accordingly, in June 1983, additional tasks were added to develop requirements characteristics for FEGS, and to determine the potential for advanced power systems to meet those needs as well.

The following sections report on the conduct and the results of the mobile power system analysis and the facility electricity generating system analysis.

C. The Technologies

APL specified ten technologies of interest for MEP applications from among the nineteen included in the ATES data base:

1) Brayton cycle engines

   a) Recuperated open cycle gas turbine (RO)

   b) Non-recuperated open cycle gas turbine (NR)

   c) Closed cycle gas turbine (CC)

2) Diesel engines

   a) Turbocharged diesel engine (TD)

   b) Turbocompounded diesel engine (TC)

   c) Adiabatic diesel engine (AD)

3) Stirling cycle engines

   a) Free piston Stirling engine (FP)

   b) Kinematic Stirling engine (KS)

4) Electrochemical systems

   a) Phosphoric acid fuel cell (PA)

   b) Solid polymer fuel cell (SP)

In order to secure specialized knowledge on the current and projected states-of-the-art in these ten technologies, Applied Concepts executed subcontracts with three hardware specialists:

1. Mechanical Technology, Incorporated (MTI), 968 Albany-Shaker Road, Latham, NY 12110. MTI is a privately owned company with a staff of over 350 technical professionals engaged in production development and contract research in engine and power systems. MTI's Stirling Engine systems Division was the coordinator of Stirling engine technologies assessments. MTI's Research and Development Division had programmatic

responsibilities for the gas turbine technologies.

2. Giner, Incorporated, 14 Spring Street, Waltham, MA 02154. Giner, Inc. is the leading small business in fuel cell R&D, with over ten years' research and development experience in the field of electrochemical energy conversion. The company undertakes all phases of electrochemical R&D, from laboratory experiments to hardware fabrication and testing, as well as analytical studies of individual processes, total systems and market analysis. Giner, Inc. had progrommatic responsibilities for the fuel cell technologies.

3. Mr. Gregory Flynn, consultant, P.O. Box 164, St. Clair Shores, MI 48083. Mr. Flynn is a widely experienced consulting engineer, providing technical services to a number of automotive and engineering clients in Europe, Asia, and the U.S. Mr. Flynn's experience was gained during 33 years of progressive responsibility at the General Motors Research Laboratories. Mr. Flynn had programmatic responsibilities for Diesel engine technologies.

When additional tasks were undertaken to consider facilities' power systems, the same ten technologies were to be compared to the new set of requirements. Although funds were not available to further develop the information contained in the ATES, the project team decided to include in the analysis five additional technology options which are appropriate for non-mobile applications. These were:

5) Wind Turbines (WT)

   a) Horizontal axis systems

   b) Vertical axis systems

6) Photovoltaic Energy Conversion Systems

   a) Flat plate P/V systems (PV)

   b) Actively cooled (concentrating) P/V systems (AC)

   c) Photoelectrochemical systems (EC)

D. The ATES

For detailed information regarding the technologies included in the MEP and FEG analyses, the reader should consult the USAF Advanced Terrestrial Energy Study , as reported in AFWAL TR 82-2019, dated April 1982. This four volume report provided the basis for the technologies studied for USAF mobile power and facilities' applications. Technology descriptions are found in "Volume I: Project Summary", as are definitions for the technical parameters which were used to characterize each technology.

Volume III of the ATES, "Parameter Survey," provided the starting point for assigning parametric values to the technology options. The three expert subcontractors were asked to review the parametric values provided in the ATES for currency and applicability to military systems. Where updated values were made available, they were provided to the Project Engineer and used in the analysis. Appendix A presents the parametric data used in this analysis and indicates where differences exist from the ATES.

E. The MCDM and MADM

The Multiple Criteria Decision Model (MCDM) is a computer model developed for APL by the University of Dayton School of Engineering, Dayton, OH 45469, during the period June 1980 - November 1981. (The final report, dated November 1981, on the MCDM is available through DTIC and NTIS publication channels as DTIC document accession number AD A119160).

The MCDM was developed to solve problems involving the comparison of alternatives with multiple attributes, according to multiple criteria. The model is capable of analyzing up to 10 different technology systems over 5 time increments. It accepts up to 20 quantitative and qualitative parametric descriptions for each technology system. The program provides a system value comparison for the technologies under consideration for the applications of interest.

The MCDM's system selection methodology identifies the optimum technology for a particular application, by comparing the descriptive characteristics (parameters) for the technologies of interest to the requirements of that application. Quantified requirements are developed external to the model, by having users of the technology rate the relative value of those characteristics to the application of interest.

The MCDM was written in FORTRAN IV. It was designed for, and runs on software of two large computer systems as maintained by the Aeronautical Systems Division (ASD). A CDC Cyber 175 computer is used for interactive support during program operation. A Cyber 74 is used for batch processing and interactive graphics. The systems are architecturally compatible and share the same permanent disk facilities and tape drives.

During the course of this research, which represented the first field validation of the MCDM, Applied Concepts' research team discovered problems in two of the algorithms' used in the MCDM. It also became apparent that the model could be made to run more efficiently. Applied Concepts offered to correct the faulty algorithms, to translate the program from FORTRAN to BASIC, and to improve and modify the program to be a menu-driven, user friendly, microcomputer based analytic tool. This proposal was accepted by AFWAL and these additional tasks were performed prior to the final analytical task.

To distinguish the microcomputer based model from the mainframe version, the newer tool was christened MADM for Multiple Attribute Decision Model. MADM is to be regarded as an improvement upon MCDM rather than a new model. In general, the procedures used in the original model are also used in the new one. The concepts and terminology related to problem design and evaluation have been retained and incorporated into MADM.

It was the utilility of the MCDM and its ability to compare unlike variables in a meaningful way which made it a unique and valuable tool. MADM builds on and extends those capabilities substantially.

Chapter IV below provides information upon the operation of MADM. Detailed information, including a program listing and examples of a sample run of the model are included in User's Manual for the Multiple Attribute Decision Model (MADM), submitted to AFWAL on June 24, 1983. Applied Concepts will also accept inquiries concerning the availability of additional copies of the model and its user's guide, from interested parties.

II. The Research Problem: Statement of Work

The following is an integrated abstract of the contractual statement of work (technical requirements) for the research project:

The contractor shall:

1) Determine near and intermediate term requirements for MEP systems.

2) Modify and improve the MCDM and develop a microcomputer based version (MADM) for conducting the analysis.

3) Assess the future utilization potential of ten advanced power system technologies, using the results of Task 1 for the requirements data base, the ATES and other data sources as the technologies data base, and using MADM as the analytical tool.

4) Determine system deficiencies in meeting requirements, where R&D might overcome those deficiencies.

5) Determine the developmental costs of R&D to overcome those deficiencies.

6) Conduct an analysis for facilities electric generating systems, by repeating tasks 1, 3 and 4 for facilities' applications.

The following sections detail the research team's approach and findings for each task.

III. MEP System Requirements Definition

A. Approach

The first step in the research was to determine the USAF mission driven requirements for MEP systems. At the beginning of this project, very little was known at the laboratory about the distribution of USAF MEP applications or about the operational requirements of those applications. A lack of generation of formal documents identifying required operational capabilities (ROC) or statements of need (SON) from MEP users has been a continuing problem, as recognized by the DoD Project Manager for Mobile Electric Power.

A major task and a major accomplishment of this research was to aggregate and make available for research, information which was previously available primarily at the using-unit level. The research team gathered information regarding USAF MEP applications from system users and managers, and then organized that information to form a descriptive data base which could be used at headquarters or planning staff levels for requirements definition.

The major resource for this task was the non-commissioned officers (NCOs) and small unit commanders in MEP operational support and maintenance units. In addition, the staffs at the Sacramento Air Logistic Center (ALC), McClellan AFB, CA, and the San Antonio ALC, Kelly AFB, TX were helpful in providing aggregate information regarding current systems' and systems' maintenance requirements. MAJCOM logistics and maintenance staffs were also valuable resources, especially for identifying using units and facilitating liaison with them.

The approach to this task heavily emphasized field research and the solicitation of professional opinion from MEP system users in USAF units. Two types of information were desired:

1) The MADM model requires quantitative input regarding requirements in the form of a "User's Preference File." This information must be quantitative, expressed as a decimal fraction between 0.000 and 1.000, with variables related on a one to one basis with the parameters in the technologies data base. This information was sought through a field survey as described below.

2) The research team felt that more detailed and qualitative information should be sought than could be obtained through the field survey. This was necessary both to structure the survey and to provide a basis for interpreting its results.

This task was therefore carried out in three major steps:

1.1 Conduct field interviews with MEP system users and managers.

1.2 Conduct a field survey of MEP system users.

1.3 Organize and analyze results.

During February and March of 1982, Applied Concepts' research team conducted interviews with MEP users and maintainers at numerous bases. During these visits MEP systems and requirements were discussed in detail, and the preliminary survey instrument was developed, modified, and validated through field testing.

Coordination and liaison visits also were conducted at headquarters and other appropriate locations to discuss the research project and to obtain technical data about MEP operating systems. The following organizations were visited by the research team:

- Field and organizational maintenance squadrons and headquarters of 317th Tactical Airlift Wing (MAC), Pope AFB, SC.

- Equipment maintenance and aircraft generation squadrons, 1st Fighter Wing (TAC), Langley AFB, VA.

- Field and organizational maintenance squadrons, 19th Bomber Wing (SAC), 42nd Air Division, Robins AFB, GA.

- The 9th Tactical Intelligence and the 507th Tactical Air Control Center Squadrons, the 682nd Air Support Operations Center, and the 507th Tactical Air Control Wing Headquarters (AFCC), all located at Shaw AFB, SC.

- 5th Combat Communications Group (AFCC), Robins AFB, GA.

- 72nd Tactical Control Flight (TAC), Fort Monroe, VA.

- Tactical Communications Division, Air Force Communications Command, Langley AFB, VA.

- Within the Aeronautical Systems Division (ASD) of Air Force Systems Command (AFSC): The Producibility, Reliability, Availability, and Maintainability Special Program Office (ASD/RAOF), and the Support Equipment Systems Program Office (ASD/AEGA) at Wright-Patterson AFB, OH.

- Sacramento and San Antonio Air Logistics Centers (AFLC).

- Headquarters, Tactical Air Command, Langley AFB, VA.

- Headquarters, Air Force Systems Command (AFSC), Andrews AFB, MD.

- Headquarters, Air Force Logistics Command (AFLC), Wright-Patterson AFB, OH.

- The Air Ground Support Equipment Working Group (AGSEWG), meeting at HQ AFLC.

- Headquarters, U.S. Air Force (AF/LEY), The Pentagon, Washington, DC.

- DoD Project Manager for Mobile Electric Power, Fort Belvoir, VA.

In addition, telephone conversations were held with other appropriate units and offices, notably Headquarters, Strategic Air Command (SAC), Offutt AFB, NE, and Headquarters, Military Airlift Command (MAC), Scott AFB, IL.

During the interview phase, the research team identified key MEP staff personnel within the MAJCOMs and in special project offices to establish a senior staff NCO as the point of contact (POC) for distribution of the surveys. The research team called all POCs to explain and answer questions about the survey questions or about the project. Subsequent to the required review and approval cycle, surveys and requests for cooperation were distributed by the AFWAL Project Engineer, to the POCs, for further distribution and return via military channels.

Once the surveys were received, it was necessary to organize the information they contained into meaningful categories and aggregates. The knowledge gained during the field visits provided the basis for defining nine applications categories or "scenarios" for analysis in Task 2. As a final step of this task, survey responses were sorted according to the application category which they represented and data was aggregated by category for the analysis.

B. Results

1. Interview Results

Figure III-1 presents an MEP system inventory summary for USAF as of mid-FY 1982. The largest single use of engine generators within USAF is the support of flightline aircraft maintenance. Three different types of generators are in use for these applications. The MEP 356A supports aircraft in the Tactical Air Forces. This light weight gas turbine system includes a compressor from which bleed air can be used to start fighter aircraft or to power subsidiary systems. The MEP 357A is a newly available diesel engine driven system whose fuel efficiency and reliability compensate for its greater weight. It is the current system of choice for SAC and MAC aircraft. Continued procurement of the MEP 357A is planned, as the obsolete MD-3 is phased out of the inventory, and as MEP 356As are limited to fighter aircraft support.

New design and procurement activities are currently underway to secure a replacement or modification of design for the MEP 356A because of its very high fuel consumption and very low mean time between overhauls. Similar activities are underway with respect to centralized aircraft support systems (CASS) within Air Training Command (ATC) and SAC. CASS, as currently concieved, are imbedded utility systems, relying on purchased power, and would require the maintenance of an MEP back-up capability.

MEP NO.	SIZE (KW)	FREQUENCY (HZ)	ENGINE TYPE	NUMBER ON HAND CONUS	NUMBER ON HAND EUROPE	NUMBER ON HAND PACIFIC	TOTAL	NUMBER SERVICEABLE
FLIGHTLINE GENERATORS								
356A	60	400	GTED	2,576	431	233	3,240	3,033
357A	72	400	DED	509	17	40	566	566
N/A(MD-3)	45	400	GED	-	-	-	2,500(E)	?
							6,306	
COMMUNICATIONS AND ELECTRONICS SUPPORT GENERATORS								
404A&B	60	400	GTED	821	280	22	1,123	1,093
024A	0.5	DC	GED	21	0	0	21	21
025A	1.5	DC	GED	614	114	0	728	706
026A	3.0	DC	GED	469	31	71	571	541
021A	3	400	GED	25	0	0	25	19
022A	5	400	GED	2	0	0	2	2
113A	15	400	DED	2	0	0	2	1
114A	30	400	DED	338	0	0	338	52
115A	60	400	DED	154	6	2	162	66
116A&B	100	400	DED	37	5	9	51	47
							3,023	
GENERAL PURPOSE GENERATORS (MISSION AND/OR HOUSEKEEPING SUPPORT)								
015A	1.5	60	GED	3	0	0	3	3
016A	3	60	GED	1,297	63	33	1,393	1,393
017A	5	60	GED	818	86	49	953	874
018A	10	60	GED	5	0	0	5	5
002A	5	60	DED	428	14	11	453	331
003A	10	60	DED	833	12	11	856	760
004A	10	50/60	DED	211*	50*	7*	414	316
005A	30	50/60	DED	922*	88*	45*	1,089	1,055
006A	60	50/60	DED	906*	142*	131*	1,247	1,179
007A&B	100	50/60	DED	412*	0*	0*	453	412
008A	150	50/60	DED	407*	61*	35*	541	503
009A	200	50/60	DED	27*	1	0	28	28
029A	500	50/60	DED	4	0	6	10	10
							7,445	
BARE BASE SUPPORT GENERATORS								
	750	50/60	GTED	26	0	0	26	26

*INCLUDES ONLY STANDARD, SERVICEABLE UNITS.

INVENTORY DATA PROVIDED BY THE SACRAMENTO AIR LOGISTICS CENTER

FIGURE III-1: USAF MEP SYSTEM INVENTORY SUMMARY AS OF MID-FY 1982

The second major USAF application for MEP systems is for the support of communications and electronics equipment. Most notably, some 1,100 MEP 404s are largely configured into power plants for the support of the Tactical Aircraft Control System (TACS).

Altogether, USAF maintains over 6,000 generators totalling 330 MW generating capacity for aircraft support, 3,000 generators totalling 95 MW generating capacity for communications and electronics systems support, 7,000 units totalling 260 MW generating capacity for general purpose applications, and 26 systems totalling 19 MW for mobile bare base support. It is these applications and the systems identified in Figure II-1 which make up the baseline for the analysis, both in terms of technologies and in terms of a comparative base for requirements definition.

Figure III-2 provides a convenient summary of the characteristics of current USAF MEP systems. This will be a useful reference for interpreting some of the results reported below.

Prior to the beginning of research, the project engineer and the research team anticipated defining USAF mission requirements for MEP systems evolving over the period 1985 - 2000. It became apparent during the field interviews that such a matrix does not correspond to the current perceptions and operational methods of USAF MEP users. The basic reason for this is institutional in nature. Current MEP equipment is adequate to support USAF missions. It is definitely true that USAF mission effectiveness and cost effectiveness can in many ways be improved by the introduction of new MEP equipment. However, such improvement is typically incremental, and therefore does not achieve the urgency or the precision of a "requirement."

For example, virtually any user of the MEP 357A, Hobart diesel engine driven generator, would state a desire or requirement for a lighter weight system. If asked to quantify the need over time, the only meaningful answer the user could give would be "as much lighter as you can make it, as soon as possible." Thus, the establishment of "requirements" reduces to an engineering problem, and the appropriate requirement is a design goal which expresses the weight which can be achieved according to the state of the art in 1985, 1990 or 2000. This is the content of the ATES.

Such engineering goals are normally the result of design trade offs. For example, the MEP 356A, gas turbine engine driven generator weighs less than half as much as the MEP 357A, but its fuel consumption is five times as high, and its mean time between overhauls is only an eighth that of the diesel system. Technology choices, therefore, will depend upon a mutual comparison and rating of important parameters.

During the field interviews, the research team identified seventeen such parameters of interest to MEP system users. Twelve of the seventeen had counterparts within the ATES data base, and thus could be entered into MADM for computer assisted evaluation. Those variables were:

UNIT (MEP#,KW/HZ,TYPE)	SIZE (LXWXH)(IN.)	WEIGHT (LBS)	MOBILITY	FUEL TYPE (10/20)	FUEL RATE (GAL/HR)	MTBF (HRS)	MTBO (HRS)	NOISE (DB@25FT)	COST/UNIT (1985$)(E)	COMMENTS
356, 60/400, GTED	117x55x67	2,800	TOWED	JP4	30-45	62	1,100	91-100	135	BLEED AIR FOR ENGINE STARTS
357, 48/400, DED	105x60x44	7,000	TOWED	D/JP5	7	250SPEC	8,000	87	29	COMMERCIALLY DEVELOPED.
(MD3), 45/400, GED			TOWED	MOGAS	8-10		SALVAGE		N/A	OBSOLETE, 28VDC CAPABILITY
404B, 60/400, GTED	(PLANT) 223x95x58	(PLANT) 5,000	MOBILI-ZERS	JP4,JP5	35		800-1,100	85	(PLANT) 328	2 MEPGS, USED AS A/E 24U-8 POWER PLANT.
114A, 30/400, DED	80x36x55	3,000	SKIDS	D/JP4	3	370SPEC		82	18.5	
115A, 60/400, DED	87x36x59	4,400	SKIDS	D/JP4	6	450SPEC		90	25	
116B, 100/400, DED	106x40x65	7,000	SKIDS	D	10	580SPEC		91	82	50K IN LARGE LOTS.
025A, 15/DC, GED	28x21x19	125	SKIDS	MOGAS	0.5	250SPEC		78	0.9	
026A, 30/DC, GED	35x24x24	285	SKIDS	MOGAS		250SPEC		79	1.8	
016A, 3/60, GED	35x24x25	285	SKIDS	MOGAS	0.9	250SPEC		79	2.0	
017A, 5/60, GED	40x30x25	488	SKIDS	MOGAS	1.4	250SPEC		82		1981 LAST PURCHASE
018A, 10/60, GED	57x30x29	850	SKIDS	MOGAS	2.4	250SPEC		82		1981 LAST PURCHASE
003A, 10/60, DED	62x30x37	1,240	SKIDS	D/JP4	1.1	500SPEC		77	$12	
004A, 15,60, DED	70x36x55	2,450	SKIDS	D/JP4	1.5	670SPEC		80	$18	
005A, 30/60, DED	76x34x55	2,850	SKIDS	D/JP4	3.0	670SPEC		82	$20	
006A, 60/60, DED	87x36x59	4,240	SKIDS	D/JP4	6.0	500SPEC		86	$22	
007B, 100/60, DED	106x40x65	7,000	SKIDS	D/JP4	8.5	580SPEC		85	$38	
009B, 200/60, DED	114x50x75	10,300	SKIDS	D/JP4	10	520SPEC		93	$60	
029A, 500/60, DED	219x88x120	34,000	SKIDS	D/JP4	37	500SPEC		86	$168	

FIGURE III-2: USAF TACTICAL GENERATOR CHARACTERISTICS

ATES Parameter	MEP Parameter Heading
Designated Fuel	Fuel Type
Annual Fuel Consumption	Fuel Consumption
Lifetime	Useful Life
Start-up Time	Start-up/Shut-down Time
System Volume	Size
Weight	Weight
Type	Other Mobility Factors
Operations and Maintenance	Operability
Reliability	Mean Time Between Failures (MTBF)
Locational Constraints	Environmental Constraints
Operational Constraints	Quality of Electric Output
Environmental Contraints	Noise
None	Level of Repair
None	Time to Repair
None	Mean Time Between Overhaul (MTBO)
None	Infrared (IR) Signature
None	Electromagnetic Interference (EMI)

The seventeen parameters (which are defined therein) became the basis for the quantitative field survey. (Figure III-3) The first four questions on the survey were used to group responses for analysis. The parameter ranking and rating values provided, in aggregate, the input to MADM. The final three discussion questions provided a means for the research team to validate its selection of parameters, and a vehicle to elicit additional information which might prove helpful to researchers and designers in the MEP field.

2. Survey Results

276 surveys were received. The response rate for the survey was nearly 70%, based upon the number of surveys returned and the number distributed, although responses were completely voluntary. This comparison is not wholly accurate, because some local reproduction is known to have taken place, as authorized in the cover letter to the survey. Nonetheless, the response indicates the high level of interest among MEP personnel in the subject area. This level of interest was confirmed by the time which most of the respondents took to seriously address the discussion questions.

Because of the constraints of the MADM program, parameter ratings had to be 100% complete and 100% properly formatted to be useable in the analysis. Approximately 85% , or 235 of the survey instruments received were completed accurately and could be used in the data base development process. Qualitative information was used from all respondents, including the 15% whose parametric responses were not capable of input to MADM.

Responses to the discussion questions confirmed an impression which the research team had developed during the field interviews: Many of the

MOBILE ELECTRIC POWER SYSTEMS REQUIREMENTS SURVEY

SURVEY OBJECTIVE: To obtain from USAF users their professional judgement regarding the relative importance of mobile electric power system characteristics. Results will be used by the Aero Propulsion Laboratory to identify areas for research and development.

1. Respondent Information:

   Unit/wing (or parent organization) ____________________

   Base ____________________

   Rank/grade ____________________

2. How many and what types of mobile electric power systems do you currently use and/or maintain?

3. What mission do these systems support?

4. What types of equipment do these systems support?

5. Using your professional judgement, and based upon your current mission responsibilities, rank order the mobile electric power system parameters on page 3 in order of their importance. (You may tear off page 3 and keep it.) Put your answers in the spaces provided on page 2. You may put either the letter codes or parameter names in the spaces provided. After you have ranked the parameters, give each a rating value. The highest ranked parameter will have a rating of 100. Rate each of the other parameters in relation to it. For example, a parameter which is half as important as the top-ranked parameter would be given a rating value of 50.

6. Please answer the questions on page 2 which follow the ranking and ratings.

- 1 -

FIGURE III-3:

MOBILE ELECTRIC POWER SYSTEM REQUIREMENTS SURVEY

	Parameter Ranking	Rating Value
1.		100
2.		
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		
11.		
12.		
13.		
14.		
15.		
16.		
17.		

Other Questions:

1. In your own words, what is the most critical deficiency in current mobile electric power systems?

2. How does this deficiency negatively impact the performance of your mission?

3. Do you have any other critical requirements not included in the list of parameters?

THANK YOU FOR YOUR PARTICIPATION IN THIS SURVEY. PLEASE MAIL THE COMPLETED FORMS PROMPTLY TO:

Valerie J. Van Griethuysen
AFWAL/POOC
Wright-Patterson AFB, OH 45433

- 2 -

FIGURE III-3 (CONT'D):

DESCRIPTION OF PERFORMANCE PARAMETERS FOR MOBILE ELECTRIC POWER SYSTEMS

A. Size. The system envelope in dimensions of length, width and height.

B. Weight. The weight of the system without fuel, coolant, lubricant, electrolyte, and optional equipment.

C. Other Mobility Factors. A qualitative assessment of the degree of mobility based on system transportability by truck or aircraft, system assembly and dismantling time, and need for prior site preparation. (Not considering size or weight per se.)

D. Fuel Type. Primary and emergency fuels which can be used without system adjustment or modification.

E. Fuel Consumption. Rate of fuel consumption, in quantity per hour.

F. Useful Life. The total expected lifetime of the system, either in use (number of hours of operation) or storage (number of years depot storage life).

G. MTBF. Power system availability for operational use in mean time between failure, in hours.

H. Level of Repair. Unit, Intermediate, or Depot Level.

I. Time to Repair. The amount of time required to repair a malfunctioning system.

J. MTBO. Mean time between overhaul.

K. Noise. The loudness and pitch of noise emitted from an operating system under normal load.

L. IR Signature. The level of infra-red radiation emitted from an operating system.

M. EMI. The level of radio frequency electromagnetic radiation emitted from an operating system.

N. Environmental Constraints. Ability to perform under extremes of temperature, humidity, altitude, weather, etc.

O. Operability. Technical training requirements for system operation and maintenance.

P. Start-up Time/Shut-down Time. Elapsed time required to bring the system to full output from a "cold start" condition. Elapsed time to bring the system from full output to an off or standby mode.

Q. Quality of Elec. Output. Variability in output parameters.

- 3 -

FIGURE III-3 (CONT'D):

concerns among USAF MEP system users regarding MEP performance and design are not dependent on the conversion technology of the system.. These concerns tend to center on design for operability, component design, component integration, and supportability of system design, especially training support. These concerns apply equally to each new technology design and to current systems, so it is appropriate to report them here. Appendix B, "Responses to Discussion Questions," contains an abstract of this information.

It is important to note that question 3 of the discussion questions (See Figure III-3) did not elicit an identification of any critical parameters which were not on the original list of seventeen. In this way, the survey is a validation of the parameter selection.

Many of the comments received in response to the discussion questions refer to one or more of the seventeen variables. These comments thus provide some narrative insight into ways in which USAF MEP users regard the importance of the seventeen variables. Figure III-4 presents a sample of comments which were specifically offered by respondents as suggestions for incorporation into future systems' design. It can be seen that most of the comments are not directly specific to any single technology. An analysis of the responses to the discussion questions shows that the parameter rating section of the survey includes all of the technology linked variables for the analysis.

Figure III-5 presents the cumulative results of the parametric ratings by MEP system users. The ratings indicate that the most important characteristic of MEP systems to USAF users is that of power output quality. Least important are electromagnetic interference and infrared emission. The most important characteristic is roughly twice as important to the group of users as is the least important. Due to preselection, totally unimportant technical characteristics had been excluded from the survey list.

In summary, the parametric information gathered by the survey was useful toward achieving the principal objective of this research which was technology assessment. The discussion questions validated the choice of parameters as generated during the field interviews. In addition, the discussion questions provided a great deal of information regarding MEP system design and system support which will be equally valid for new technology designs as for current technology designs, and therefore should be considered by system developers in all technology areas.

In order for user preference data to assume its full meaning as a basis for requirements generation, it is necessary to consider the data from an applications standpoint. Section III B 3, below expands the consideration of the parametric data base.

- SMALL MEP UNITS SHOULD BE SMALL, COMPACT LIGHT-WEIGHT, AND EASY TO CAMOUFLAGE.
- MEP ENGINES SHOULD HAVE A MULTI-FUEL CAPABILITY TO INCLUDE LOW OCTANE FUELS, WHICH MAY BE THE ONLY FUEL SOURCE LOCALLY AVAILABLE OCONUS.
- THE MEP FUEL TANK CAPACITIES SHOULD BE ENLARGED TO SUSTAIN CONTINUOUS OPERATIONS.
- THE SYSTEM'S CRITICAL COMPONENTS SHOULD BE PROTECTED FROM DAMAGE BY SAND OR DUST.
- THE ENTIRE MEP UNITS SHOULD BE EASILY ADAPTABLE TO EXTREME ENVIRONMENTAL CONDITIONS, PARTICULARLY HEAT, RAIN, SAND AND COLD TEMPERATURES.
- POWER CABLES SHOULD BE DESIGNED TO BE EASILY CONNECTED AND DETACHED AND CONNECTORS SHOULD BE STANDARDIZED FOR INTERCHANGEABLE USE.
- A SYSTEM SHOULD BE DEVISED TO ENHANCE REFUELING WHILE OPERATING.
- MEP UNITS FOR THE TACTICAL AIR REQUEST NET SHOULD FIT INTO OR BE MOUNTED IN THE REAR OF THE M151 JEEP OR ITS SUCCESSOR.

FIGURE III-4:

SUGGESTED IMPROVEMENTS FOR FUTURE MEP EQUIPMENT

FROM MEP USERS SURVEY

MEP SURVEY RESULTS

ANALYSIS GROUPING: ALL RESPONDENTS

NO. OF RESPONDENTS IN GROUP - 235

PAR CODE	PARAMETER DESCRIPTION	PARAMETER RATING
Q	OUTPUT QUALITY	78.06
O	OPERABILITY	69.81
I	TIME TO REPAIR	69.65
G	MTBF	66.21
N	ENVIRON CONSTR	65.75
E	FUEL CONSUMPT	64.82
H	LEVEL OF REPAIR	60.83
P	START/STOP TIME	57.88
K	NOISE	55.94
C	OTH MOB FACTORS	55.75
A	SIZE	54.51
D	FUEL TYPE	54.26
F	USEFUL LIFE	53.51
B	WEIGHT	53.39
J	MTBO	45.69
M	EMI	36.18
L	IR SIGNATURE	34.83

FIGURE III-5

3. Organization and Analysis Results

The research team designed a computer based statistical program in order to organize parameter rankings of different combinations of respondents according to the identifying information on page 1 of the survey (Fig. III-2). This program computed and presented statistical output , in the form of "MEP Survey Results" sheets, i.e., users' preference profiles, for the following groups of respondents.:

1) Type of Survey Participant

a) All Respondents
b) Officers
c) NCOs
d) Jr. Enlisted Personnel
e) Civilian Employees

2) MAJCOMS

a) TAC
b) SAC
c) MAC
d) USAFE
e) PACAF
f) AFCC
g) AFSC

3) Flightline Personnel

a) Flightline Summary
b) Flightline Officers
c) Flightline NCOs

4) Maintenance Squadrons

a) OMS, Organizational Maintenance Squadrons
b) FMS, Field Maintenance Squadrons
c) EMS, Equipment Maintenance Squadrons
d) AGS, Aircraft Generation Squadron
e) CRS, Components Repair Squadrons
f) AMS, Avionics Maintenance Squadrons
g) MMS, Munitions Maintenance Squadrons
h) CAMS, Consolidated Aircraft Maintenance Squadrons

5) Tactical Air Control System (TACS) Personnel

a) TACS Summary
b) TACS Officers
c) TACS NCOs
d) TACS Jr. Enlisted Personnel

6) TACS Organizations

   a) TACPs, Tactical Air Control Parties
   b) FACPs, Forward Air Control Posts
   c) CRC/Ps, Command & Control Centers/Posts

7) MEP Equipment Rated by Users and Maintainers

   a) MEP 356A
   b) MEP 357A
   c) MD-3 Generator
   d) A/E 24U-8 Power Plant using MEP 404 A/Bs
   e) General Power Support Generators

8) Other

   a) "Bare Base" and "Harvest Bare"
   b) Mobile Combat Communication Group

The results of these different aggregations of data are presented in Appendix C. Figure III-6 presents summary information regarding parametric evaluation according to mission area and MAJCOM. As can be seen, there is a certain amount of variation in the results according to mission area.

For the purpose of technologies assessment in Task 2, it was necessary to aggregate information according to applications scenarios. A consideration of inventory data as presented in Figure III-1 together with the survey responses led the research team to define scenarios for analysis as follows:

Power Level and Type	Application
5 kW Precise	Tactical air control parties
5 kW Utility	General purpose
60 kW Precise	Flightline
60 kW Precise	Tactical air control system
60 kW Utility	General purpose
100 kW Precise	Future flightline/electronics
100 kW Utility	General purpose
250 kW Utility	General purpose
750 kW Prime	Bare Base/ Harvest Eagle

Because ATES data was available for this system, 250 kW was chosen to represent large utility power systems, although 200 kW and 500 kW are the standard USAF sizes.

	ALL	FLIGHTLINES										
PARAMETER	RESPONDENTS	TAC	SAC	MAC	USAFE	PACAF	AFCC	AFSC	ATC	TACS	BARE BASE	UTILITY
OUTPUT QUALITY	1	1	1	1	1	1	3	2		1		
OPERABILITY	2	3		3			1	1	2			1
TIME TO REPAIR*	3	2			2	3		3		2		2
MTBF	4					2	2		1			
ENVIRONMENTAL CONSTRAINTS	5		2		3							3
FUEL CONSUMPTION	6		3	2						3		
LEVEL OF REPAIR*	7								3			
START/STOP TIME	8											
NOISE	9											
OTHER MOBILITY FACTORS	10										3	
SIZE	11										1	
FUEL TYPE	12											
USEFUL LIFE	13											
WEIGHT	14										2	
MTBO*	15											
EMI*	16											
IR SIGNATURE*	17											

*PARAMETERS INCLUDED IN THE SURVEY BUT NOT INCLUDED IN THE ATES

NOTE: A SCORE OF 1 IS THE MOST FAVORABLE SCORE.

FIGURE III-6:

PARAMETRIC RANKINGS BY THE MAJOR COMMANDS AND OTHER MEP USING ORGANIZATIONS

IV. MCDM Improvement

A. Approach

During the course of research, the research team found two problems with the algorithms as programmed for the MCDM. One of these involved an inversion algorithm which rationalized parametric values to a common basis. This was a simple problem which was readily corrected.

The more important change involved the way in which the scale for measuring the relative values of a parametric variable was set. The MCDM established a scale from 0 to 1 for each variable, with 0 being assigned to the lowest measured value for a parameter in the subsystem and 1 to the highest. All other, intermediate values, were given a relative, scalar value between 0 and 1. This meant that anomalous outputs sometimes resulted when atypical values within a system were characteristic of a subsystem being studied. It also meant that different subsystems would have different scales, since the model constructed a new scale for each parameter of each set of subsystems, based upon the unique values for the parameters within that set. Thus, there was no basis for intercomparability between model runs for different sets of subsystems.

The scaling algorithm was improved to be consistent with the normal process of decision making, as described in section IV B, below.

In addition to the necessary changes in MCDM's logic, the reasons for MADM's evolution were primarily practical. MADM is much easier to use. It can be used without training by any analyst. It is micro-computer based, menu driven, and user-friendly; where the MCDM required training to operate, and access to a main-frame computer. MADM allows an analyst to redefine his problem or his data at any time. The MCDM required that the entire model be re-run for each new problem or data change.

It was the utility of the MCDM and its ability to compare unlike variables in a meaningful way which made it a unique and valuable tool. MADM builds upon and extends those capabilities substantially. The following section is an edited abstract from the User's Manual for the Multiple Attribute Decision Model (MADM), which describes the operation of the model as applied to the problem at hand.

B. Results: Operation of the Model, Inputs, Outputs and Algorithms

MADM works by calculating a general value of comparison for systems of interest, by summing across a set of weighted comparisons of individual characteristics of the systems. The characteristics are called parameters, and are stored as data in a PARAMETER file. The weighting factors are called utility factors and are stored as data in a USER'S PREFERENCE file. These input values must be developed and entered into the model by the analyst. For the research at hand, the PARAMETER file was compiled using the amended ATES data base as presented in Appendix A. The USER'S PREFERENCE file was compiled using the results of the MEP survey as presented in Appendix C.

The outputs of the model are the overall relative ranks (system utility) for the systems being studied. The algorithmic logic of the model is an additive, multiparameter one of the general form:

$$U_s = k_1 u_{1,s} + k_2 u_{2,s} + \ldots + k_n u_{n,s}$$

where:

1) U_s is the utility value for system s

2) the set of $\{u_1, u_2, \ldots, u_n\}_s$ are normalized utilities representing the utility contributions of parameters 1, 2,...,n for each system, s, under consideration

3) the coefficients $(k_1, k_2, \ldots, k_n)$ are measures of the importance of each parameter as derived from the professional judgements of the users.

The values k_n are normalized values derived from data contained in the USER'S PREFERENCE file. This file is also referred to as the SCENARIO file, because the user's preference should depend on a set of assumptions regarding the conditions of use to which the technology is to be put. Thus, the values for $\{k_n\}$ are valid for one application scenario. For the purpose of this discussion we shall not distinguish between k_n's which are normalized, and the unnormalized values which reside in the SCENARIO file.

The values of k_n are to be determined relative to one another, and expressed on a scale of 0 to 1. Care must be taken that each user preference k_n is closely related to each parametric utility value u_n. This means that each parameter, n, must be defined for the persons providing values for $\{k_n\}$ in the same way they are defined for the persons determining the values for the system technical parameters $\{u_n\}$.

Any number (n) of parameters can be used, within the memory limitation of the computer. In this research, twelve parameters were used in the analysis, since this is the set of parameters which were both available in the ATES and found to be important to USAF MEP users through the interview and survey process.

There are some practical considerations in obtaining a valid set of values for $\{k_n\}$:

First, MADM will accept only values between 0 and 1 for each k_n. There seems to be a perceptual problem in getting people to assign values on this scale. One good solution, developed during the interviews, is to ask users to assign values between 0 (worst) and 100 (best), and later, divide all answers by 100. This was the procedure used in this research.

If k_n's are to be sought from multiple sources, it is important for later comparison that they be using similar scales and criteria to assign values. One successful method, developed during the interviews, is to instruct contributors to assign the value of 100 to the most important parameter, and to let 0 represent total indifference. All other parameters can be then assigned a relative rank. Even when respondents give different parameters the highest priority, the scale is still meaningful, being a scale of importance to the user from most important to unimportant. (Problems of perception arise if 0 is assigned to least important rather than indifference). Note that the sum of k_n is not fixed. If all parameters were equally important, the value of each would be 100.

The values $u_{n,s}$ are contained in the PARAMETER file for each system or subsystem, s, and for each parameter, n. Care must be taken in defining the parameters to note whether they are normal or inverted. "Normal" parameters (contrary to the natural bias) are those in which the smallest value is most desireable. Examples include, for mobile electric power sysems, weight, fuel efficiency, noise, start up time, etc. Parameters to be inverted during the creation of a HEADER file, are those in which the largest value is more desireable, e.g. mean time between failures. This is an important factor to bear in mind in creating ordinal and either/or types of parameters.

Since MADM could not deal rationally with raw data for the u_n's, the values are normalized for each scenario. The analyst should be familiar with how this works in order to avoid misuse of the model.

In creating the PROBLEM file, the analyst will be given a choice of a default scaling strategy, or of selecting one of three strategies, including the default method, for each parameter u_n. The default method, as explained below, is a compromise between conceptual rigor and ease of application. Therefore, it is inappropriate under certain circumstances:

1) When an answer (utility value) is sought which is meaningful in terms of all possible solutions to the problem, but when the data base in the PARAMETER file for one or more $\{u_n\}$'s is atypical of the universe of values. In this case, the analyst should choose to enter "I"nput end points during the New Problem Definition File Program. This option should also be chosen for any scale whose origin is other than zero. Coordinates should be shifted to zero if negative numbers are involved.

2) When an answer is sought which is to have no external referents, but to be based only upon the range of data in the problem at hand. In this case "R"elative should be entered.

When "D"efault is selected for a scale, the Problem Evaluation Program of MADM will automatically set the largest value for the parameter found in the PARAMETER file ($u_{n,1}$) to equal 1. The normalized value of all other $u_{n,s}$'s will then be calculated according to the equation:

$$u_{n,s} = \frac{(\text{Parameter value})_{n,s}}{(\text{Parameter value})_{n,1}}$$

for each $u_{n,s}$. This means that the endpoints of the scale are 0 and (parameter value)$_{n,1}$ normalized to 0 and 1. If the parameter, n, is one in which a higher value is more desireable, be certain that the parameter has been labelled as inverted in the HEADER file. The default value should be used if the analyst is confident that the parameter is scalar, with 0 a meaningful minimum. Its use assumes that the other endpoint of the scale is validly represented by the largest value in the PARAMETER file.

When "R"elative is selected, MADM will select the largest value in the parameter files $u_{n,1}$ to equal 1, and the smallest value in the parameter file, $u_{n,t}$ to equal 0. In this case, the normalized value for the $u_{n,s}$ is given by the equation:

$$u_{n,s} = 1 - \frac{(\text{parameter value})_{n,1} - (\text{parameter value})_{n,s}}{(\text{parameter value})_{n,1} - (\text{parameter value})_{n,t}}$$

When "I"nput end points is selected, MADM will assign a value of 1 to the high end of the scale assigned by the analyst, and a value of 0 to the low end. In this case,

$$u_{n,s} = \frac{(\text{high end}) - (\text{parameter values})_{n,s}}{(\text{high end}) - (\text{low end})}$$

These scaling options need to be considered in research design.

As a final note, limits may be set to parameters, when exceeding or failing to reach a certain value is considered grounds for elimination from further consideration. This operation is exercised in the Create Problem Program. Detailed information on MADM is contained in the User's Manual as referenced above.

V. Technologies' Assessment

A. Approach

The potential operational effectiveness of the ten technologies of interest were tested against USAF requirements in nine applications scenarios using MADM, as described above. The research team also forecast the potential cost effectiveness of each of the competing technologies, using the modified ATES data for new technology options, and ALC provided data for the baseline technologies.

Life cycle cost (LCC) calculations were based upon a normalized 20 year operating period, i.e., system acquisition costs were normalized for 20 years for technologies having less than a 20 year useful life. The analysis assumes a common salvage value, set at zero, and no fuel price escalation above general inflation. Thus, any resumption of fuel price increases will only serve to favor the cost effectiveness of fuel efficient, advanced technology systems.

This means that the results of this analysis are the most conservative results based upon the most conservative assumptions. All statistics are expressed in constant 1980 dollars. The applicable GNP deflator was used when appropriate.

Previous energy system analyses for military applications have not always integrated realistic duty cycle data. As a result, some analyses have overstated the value of renewable energy systems and highly fuel efficient technologies which also have a very high procurement cost. Cost effectiveness is very sensitive to duty cycle assumptions because fuel costs tend to be the most important cost factor.

As a result of interviews with USAF MEP managers, the research team estimates that typical MEP units operate on duty cycles which aggregate to one-eighth of the total possible annual operating hours. Therefore, our analyses calculated system life cycle costs based upon this assumption. Thus, the LCC values reported in this study are different from those LCC values in the ATES, which assumed a different duty cycle, even though the same component values were used for acquisition cost, O&M costs and fuel costs on a dollar per gallon basis. The following formula was used in determining the life cycle cost for 20 years, using the statistical data as presented in the ATES.

$$LCC_{20} = 20\left\{ \frac{\text{System (Acquisition Cost)}}{\text{(System Lifetime)}} \quad \left(\begin{matrix}\text{Annual} \\ \text{O\&M Costs}\end{matrix} \right) \quad \frac{\text{Annual Fuel Costs}}{8} \right\}$$

$$\text{Annual Average LCC} = \frac{LCC_{20}}{20}$$

B. Results

1. General Considerations.

It is important to note that the data bases and the methodological tools used to generate analytical results have a much broader applicability than that reported in this report. In all cases, the research team has made its assumptions and its selections -- of variables, of scenarios, and of methods of presentation of results -- based upon the objectives of the sponsoring agency. The utilitarian pupose of this research is to identify where USAF R&D expenditures might best result in energy systems which will have the greatest value to USAF users. Other sections of this final report are meant to be supportive of broader applicability of the tools and information developed during the course of research. This section concentrates on the derivation of results which will be useful to AFWAL in its R&D mission.

Detailed analytical results for comparative system utility and comparative system life cycle costs in USAF MEP applications are presented in Appendices D and E, respectively. These analyses include data points for systems as might be procured in the years 1985, 1990 and 2000 for use over a twenty year lifetime. Variation over time, as expressed in the analytical results, is due to presumed technological development in the interim. The analysis factors out all other bases for variation over time, in order to make the meaning of the results more transparent and to reduce the sensitivity of results to prophetic assumptions.

The major external factor which could impact cost results is that of a new round of rapid fuel price escalation. This would have a differential impact on the technologies under consideration, favoring the more fuel efficient systems. A second external factor which would impact results is a change in the duty cycle of MEP equipment. The most likely senarios for such a change are scenarios of mobilization and war. Any condition which increases system utilization would also favor more fuel efficient systems. An approximation of the differential impacts on cost effectiveness under such senarios can be estimated or calculated using the data provided in Appendix E. The research team assumed a peacetime scenario as appropriate for cost effectiveness analysis, under the rationale that this criterion became secondary to other factors in the event of mobilization or war.

The potential impacts of external factors and events on operational effectiveness or on system utility are more difficult to predict or summarize. One important area is that of system reliability and durability as expressed by the parametric variables of mean time between failure (MTBF) and mean time between overhaul (MTBO). In the case of current MEP systems, for example, this would surely favor diesel engine systems over gas turbine systems in smaller sizes. Lacking historical data from actual field experience, however, it would be hazardous to predict the differential impact of alternative scenarios on new technology systems.

To serve as an aid to the interpretation of analytical results, the research team has included a baseline for comparison in each scenario. For USAF flightline generators, two baseline systems are included, since two systems are now in common use.

The reader will note that baseline results do not vary over time. This is not meant to imply that current systems are not capable of improvement. Baseline values were puposely held constant to provide a meaningful basis for the evaluation of results over time. This means that new systems for 1985, 1990 and 2000 are in all cases compared to the 1982 version of the baseline technology.

The potential of current diesel and gas turbine technologies for improvement through R&D are represented by certain of the new technology options. Non-recuperated open cycle gas turbine engines, abbreviated NROC or NR in the charts, represent improvements to the current gas turbine baseline systems. Improvements to current diesel engine driven generators are represented by turbocharged, turbocompound and adiabatic diesel engine systems. The potential for improvement in these as in all other categories can thus be projected by reference to the constant baseline systems.

Appendices D and E present quantitative projections for operational and cost effectiveness in three timeframes. The individual scenario summaries as presented below concentrate upon year 2000 comparisons. Given the twenty-year life cycle of MEP equipment, the general adequacy of current equipment, the expectation of continued technological improvement over the period, and the fact of limited USAF R&D funding resources, the research team does not believe it to be adviseable to establish multiple generation technology development programs for 1990 and 2000. By using the year 2000 projections of operational and cost effectiveness as a benchmark, sound R&D investment programs can be structured to generate utilitarian results to be realized in the introduction of new technology alternatives over the period 1985 - 2000.

Simplicity and comprehensibility of results are also promoted by this approach. Any reader desiring more detail regarding the time variable will find all of the appropriate information clearly presented in the appendices.

2. Precision of Results

The projection of future trends is an inherently imprecise activity. The research team has taken care to minimize imprecision through the following steps:

1) Minimizing contingent assumptions.

2) Applying common assumptions and methods to all systems and scenarios.

3) Double checking technology data with experts in the fields. Countervailing biases have been minimized by dealing with professionals who are "advocates" for each technology group, and by challenging any apparent exaggerations.

4) Field testing the instrument which was used to develop user preference profiles.

5) Finally, the research question is one which is tolerant of imprecision. AFWAL is interested in technology development as a participant, not as a contingent actor or observer. For this reason, the real futures' question for AFWAL is not, "Will this state-of-the-art be achieved by the year 2000?" Rather, the question is, "Is it a realistic goal for us to attempt to achieve this state-of-the-art by the year 2000?"

Thus, AFWAL can proceed to undertake or support technology development toward a particular cost and operational goal, based upon the best, albeit imprecise, available projection. As conditions change, as breakthroughs appear, as the future occurs and knowledge becomes more precise, AFWAL can adjust its programs accordingly.

No adequate methodology exists to quantify the cumulative imprecision of this analysis. It is the intuitive judgement of the research team that technology and user preference imprecision combined introduce a variation of about $\pm$ 25% to operational effectiveness values for new technology systems in comparison to baselines. The estimation of technology dependent costs and the cumulative impact of cost assumptions probably introduce a similar imprecision to cost comparison. Baseline system values are more precise than new technology values because they are based on measured quantities.

We believe that other external factors will generally affect analytical results in a consistent way. The occurrence of any dramatic technological or cost event, however, should be the stimulus for a reexamination of results in the light of the new information. Smaller, cumulative changes in parameter values should be incorporated into regular updates of the analysis on a biannual or triannual basis.

3. Results of the Analysis

The following figures (V-1 through V-9) present a graphic summary of results of year 2000 comparisons of ten technological options in nine scenarios representing USAF MEP applications. A brief narrative is presented in Sections a) though h) below, keyed to each graph. In each case, information is presented only for those technologies which exhibited a potential for improved operational effectiveness over the baseline system by the year 2000.

Information in the nine figures is presented as a comparison (ratio) with the baseline case of projected operational and cost effectiveness of the technological alternatives. Thus, an operational effectiveness of 2.0

indicates that the utility value for the system, as calculated by MADM, was twice the value of the baseline. A cost effectiveness value of 2.0 indicates that the life cycle cost of the system was calculated to be half that of the baseline. This inversion of cost values, where relative cost effectiveness is taken to be the inverse of relative cost permits a readily interpretable graphic presentation wherein a high score is always good, and a low score is always bad.

The use of ratios for comparison implies that baseline values are always 1.0. In the case of flightline systems, where two baseline systems exist, the diesel engine driven baseline was arbitrarily used for the comparison.

One important question which this analysis cannot authoritatively answer regards the relative worth of operational effectiveness and cost effectiveness. It is a mistake to assume that any linear relationship exists, e.g. that doubling operational effectiveness is worth twice the cost. In some cases achieving a ten percent improvement in operational effectiveness might be worth a tenfold cost increase. In other cases, where systems are judged wholly adequate to their use, a tenfold improvement in performance may be operationally valueless.

Based upon our field interviews with using units, the research team understands that there is a general perception that MEP systems should be improved, and that it would be worth some additional cost to achieve those improvements. This is especially true in mission essential applications such as flightline and electronics/communications support.

As a consequence of these considerations, the following general guidelines have been used to interpret the analytic results:

1) The best technological alternatives are those which indicate a potential for both operational and cost effectiveness improvements over the baseline.

2) Systems which exhibit the potential for operational effectiveness improvements at a competitive cost are also of interest.

3) The inherent imprecision of the analysis is such that a leeway of approximately 25% should be allowed in interpreting results.

a) 5 kW Tactical Precise and Utility Applications:

There were no differences in the results for these two applications scenarios, within the limits of precision of the analysis. This indicates that applications factors are less important than technological factors in this size range.

The MEP 002A, a relatively new 5 kW diesel engine driven generator, was used for the baseline system for both application scenarios since there are currently no 5 kW precise systems in the inventory. It is our understanding that gasoline engine driven systems such as the MEP 022A are to be phased out of the inventory in favor of the diesel engine alternative.

Four technology options indicate a high potential for enhanced operational and cost effectiveness in comparison to the baseline. These are free piston Stirling engines (FP), kinematic Stirling engines (KS), turbocharged diesel engines (TD), and phosphoric acid fuel cells (PA). In addition, solid polymer fuel cells (SP) show a high potential for increased operational effectiveness, but at a cost which may still be several times that of the current technology in the year 2000.

Turbocharged diesel engines may be considered to be a logical development of the baseline technology. As figures V-1 and V-2 indicate, future cost reductions are anticipated, primarily through increased fuel efficiency. Operational improvements in addition to increased fuel efficiency include reductions in system volume, improvements in the quality of power output, and reductions in environmental constraints.

The most attractive technology alternatives for applications in the 5 kW range are free piston Stirling engines (FPSE) and phosphoric acid fuel cells (PAFC). Fuel cells should become commercially available by 1985. Free piston Stirling engines are expected to become available by 1990.

FPSEs have a high potential cost effectiveness. They are currently conceived to be low cost, low maintenance, fuel efficient systems. Phosphoric acid fuel cells are projected to have similar procurement and fuel costs, but somewhat higher maintenance costs than FPSE systems.

For these technologies, cost comparisons are duty cycle dependent. If duty cycles of 2200 hrs/yr are assumed instead of 1100, fuel cells become the cost-favored system. For the purposes of this study it is fair to state that the two technologies are equally attractive for small MEP system applications.

Although FPSE and PAFC systems show similar values for projected operational effectiveness, their operational characteristics are quite different. When weighed against user preferences in USAF applications, however, the various potential advantages balance out.

In general, kinematic Stirling engines are expected to resemble free piston systems in their performance, and solid polymer fuel cells should resemble phosphoric acid fuel cells. The projected lower cost effectiveness for kinematic Stirling systems is primarily due to the potentially low procurement cost of the simple, light-weight free piston design. It remains to be proven, of course, that this potential can be realized, although substantial development is now underway in this technology area.

The low projected cost effectiveness for solid polymer fuel cells in

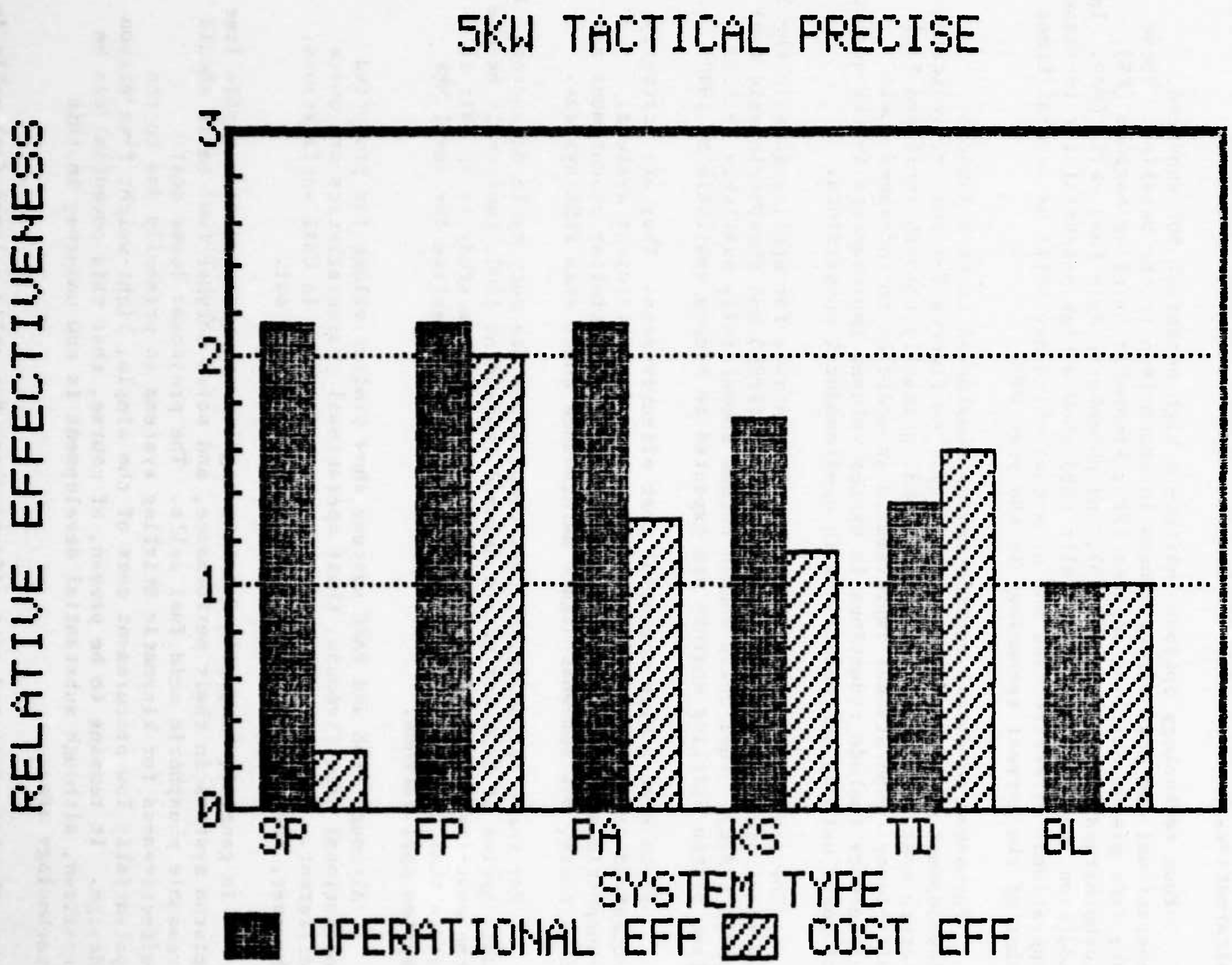

FIGURE V-1: 5KW TACTICAL PRECISE

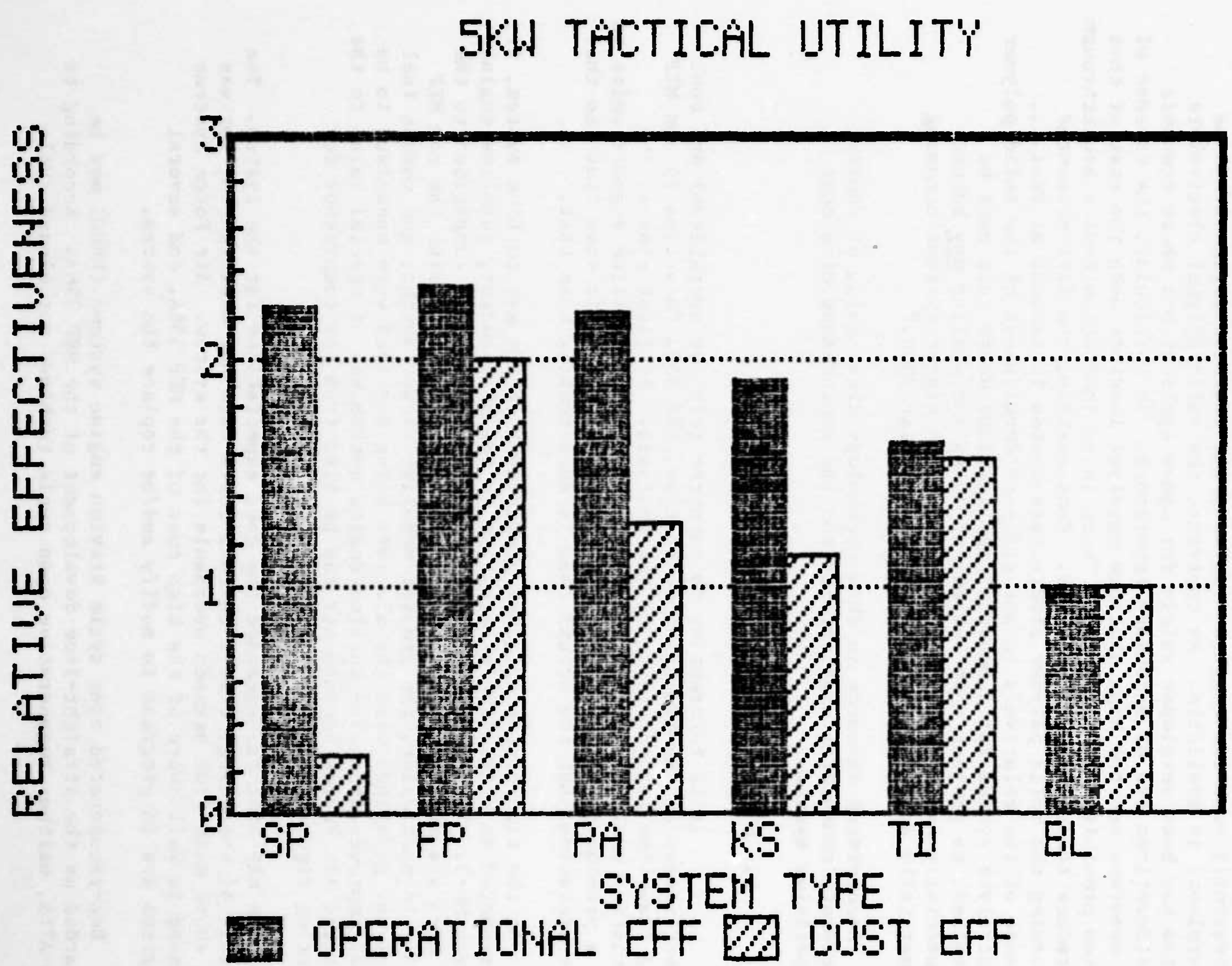

FIGURE V-2: 5KW TACTICAL UTILITY

the 2000 time frame is the result of the research team's belief that this is the earliest date for commercial availability. Giner, Inc. reports:

"Research regarding the commercial application of the phosphoric acid fuel cell powerplant has been ongoing since the late sixties and consequently much information regarding the characteristics of these powerplants is available. By contrast, the solid polymer electrolyte system has been developed solely for space applications where economic considerations are of secondary importance. In particular, the expense of the membrane and the high platinum catalyst loadings make the cost of this system prohibitively excessive. There is no indication that a breakthrough to reduce these costs is probable. Consequently, the data presented regarding the solid polymer electrolyte system is tenuous at best.... Because of the relatively infant state of development of the solid polymer electrolyte system for commercial applications where cost must be minimized, we project that systems of 30 kW and smaller may become commercially available by the year 2000 with bigger systems becoming commercially available sometime after the year 2000."

Accelerated research in this technology area could, of course, accelerate commercial availability and the achievement of a cost competitive system.

b) 60 kW Flightline Applications:

It is interesting to note the relative operational and cost effectiveness of the two baseline systems, MEP 356A (Baseline 2) and MEP 357A (Baseline 1), according to the analysis. At first glance, the statistics would indicate a willingness by USAF flightline support units to pay a premium price for improved performance. There is some truth to that interpretation, but the actual case is more complex than that.

At the time of the original procurement of the gas turbine system, it represented an attractive alternative to the obsolescent, gasoline engine driven MD-3. The relative operational effectiveness in comparison to the old MD-3 was substantially greater than the comparison with the new MEP 357A. In particular, the greater mobility, lower weight, and common fuel (JP-4 vs. gasoline) with the aircraft being serviced were conceived to be major improvements. The turbine engine system was of special value to the Tactical Air Forces because air can be bled from the compressor for starting fighter engines.

The MEP 356A far exceeded the cost expectations for the system. The impacts of the energy crisis on fuel costs were not anticipated, nor was the short mean time between overhauls for the system. Air Force Systems Command is well aware of the high cost of the MEP 356A, and several programs are in progress to modify and/or replace the system.

Non-recuperated open cycle Brayton engine systems (NROC) may be regarded as the straight-line development of the MEP 356A. According to the ATES, neither regenerative open cycle turbines nor closed cycle turbines can be expected to be commercially available in this intermediate size range, although this could be changed by a USAF R&D program, or by future decisions by auto makers as a result of automotive gas turbine development.

Turbocharged diesel engines may again be regarded as a further development of today's diesel engine driven systems as represented by the MEP 357A. Turbocompounded and adiabatic diesel engines are also anticipated only in the larger system sizes. The principal reason for this is that automotive engine development is expected to concentrate on larger sizes.

Free piston Stirling engines and solid polymer fuel cells are expected to be available only in sizes smaller than 60 kW in 2000.

Figure V-3 indicates that improvements can be expected in both of the baseline technologies. In the case of NROC turbines, better designs with increased fuel efficiency and reduced maintenance costs should permit increased operational effectiveness at a reduced cost. Turbocharging can result in more efficient, lighter-weight diesels, but at a corresponding increase in system price. In order for the increased fuel efficiency to result in increased cost effectiveness, the duty cycle for MEP systems would have to exceed the 1100 hours/year which this study assumed.

Kinematic Stirling engine (KSE) systems and phosphoric acid fuel cells (PAFC) seem to offer the best potential for increased cost and operational effectiveness in flightline applications. Both systems are expected to have fuel costs nearly half that of the baseline diesel. The purchase price and maintenance costs of the new technology systems are expected to be higher than the well-known diesel engine alternative. Overall life cycle costs for the three systems, (PAFC, KSE, and baseline), however, are the same, within the limits of precision for the analysis.

Both PAFC and KSE alternatives offer potential operational improvements over the baseline, however, as does the turbocharged diesel system. All three have a potential to reduce logistical fuel support in half. Turbocharging and fuel cells with in-stack reformers can reduce system weight and size. Both fuel cells and KSE systems would reduce flightline noise. Electrochemical systems are expected to be simple to operate, although start-up time would increase, and system lifetime would be lower than for diesel engine systems. These three technologies exhibit an overall potential, therefore, to increase operational effectiveness by 40 to 80 per cent with little or no net increase in system life cycle costs.

c) 60 kW Tactical Precise:

The baseline system in this application scenario is the MEP 404B, as part of the A/E 24U-8 Power Plant. This is the basic generator in support of the Tactical Air Control System (TACS). As can be seen from Figure V-4, the current system must be considered a very effective one, in that alternative systems do not seem to offer dramatic increases in operational effectiveness.

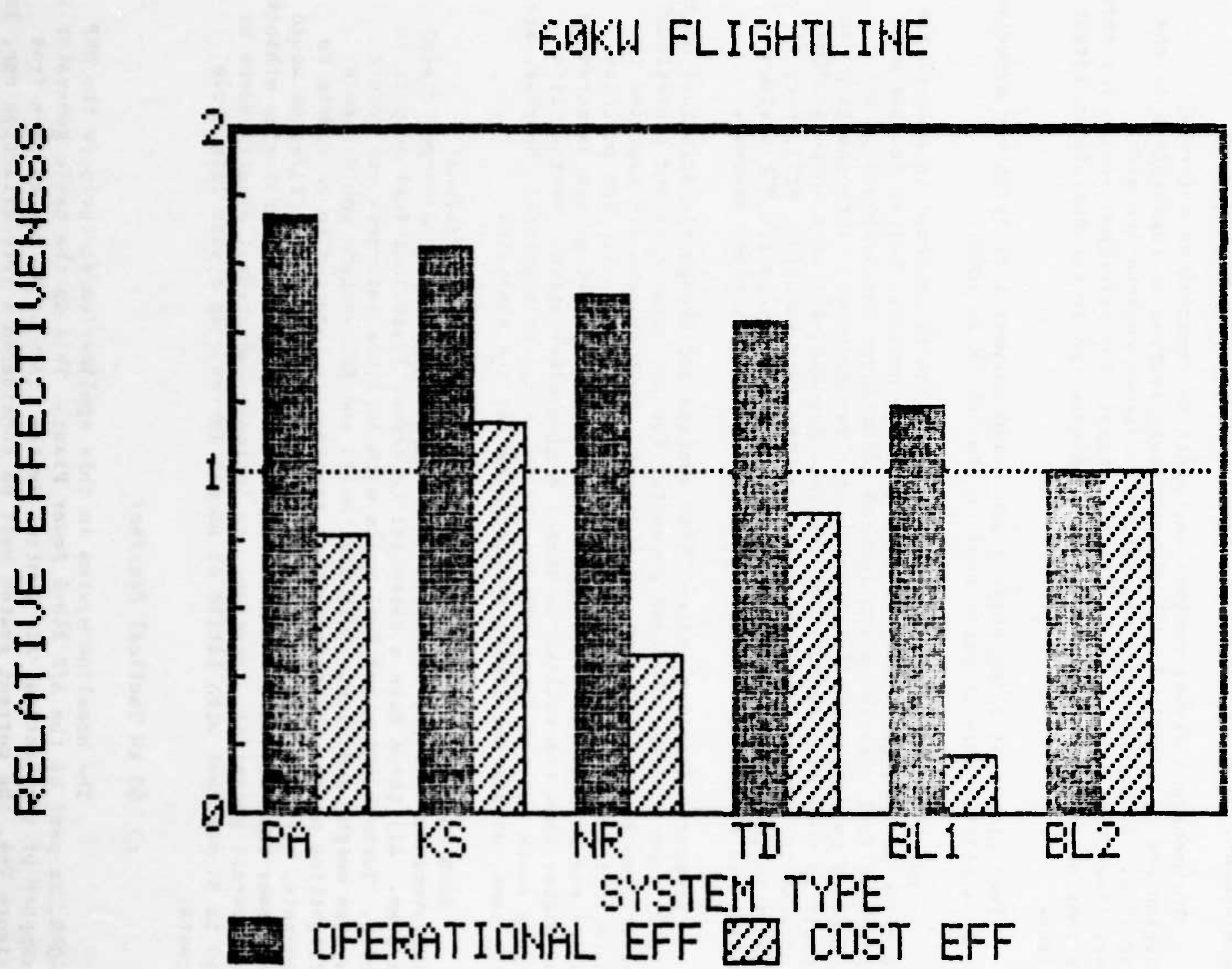

FIGURE V-3: 60KW FLIGHTLINE

The potential for increased cost effectiveness, while retaining the overall operational effectiveness of the current system, is substantial. USAF TACS experience with the MEP 404B has been similar to that with the MEP 356A. Both of these NROC systems have exhibited very high fuel consumption and low mean time between overhauls. These facts are expressed in the form of high life cycle costs.

As is the case for flightline users, action is underway to secure a replacement for the current power plant. The research team understands that a diesel engine driven generator is under consideration for this application.

Figure V-4 indicates that more cost effective NROC systems are possible, but turbocharged diesels, kinematic Stirling engines (KSE) and phosphoric acid fuel cells (PAFC) all exhibit a potential for increasing life cycle cost effectiveness by a factor of about 3:1, while maintaining or slightly increasing operational effectiveness.

d) 60 kW Tactical Utility:

The MEP 006A was the baseline for this application. Figure V-5 indicates that new technology systems are not expected to result in greatly improved operational or cost effectiveness in these applications. If PAFC, KSE or turbocharged diesel systems are developed for the other applications in this size range, then some benefit may be derived from the collateral use of the technology in these general-purpose, intermediate sized systems.

e) 100 kW Tactical Precise (Figure V-6):

The growing use of sophisticated avionics equipment is expected to increase the size requirements for support power plants. The B1-B is expected to require a 100 kW precise system, the first aircraft to move beyond the 60 kW range. Certain communications and electronics applications also exist.

In addition to the technologies considered for smaller scale applications, two other types of system are expected to become available in this size range. Turbocompounded diesel engines and recuperated open cycle turbines (ROC) are expected to become available as they are developed for automotive and other power applications.

All six technologies show the potential for operational improvements over the baseline, which is the MEP 116 diesel engine driven generator. Turbocompounding is expected to add to the procurement and maintenance costs of diesel engine systems an amount greater than the resulting fuel savings at the current low duty cycle. Turbocharging will apparently meet the requirements of the application as well as turbocompounding, at a lower cost. The low duty cycle still does not seem to justify the expense.

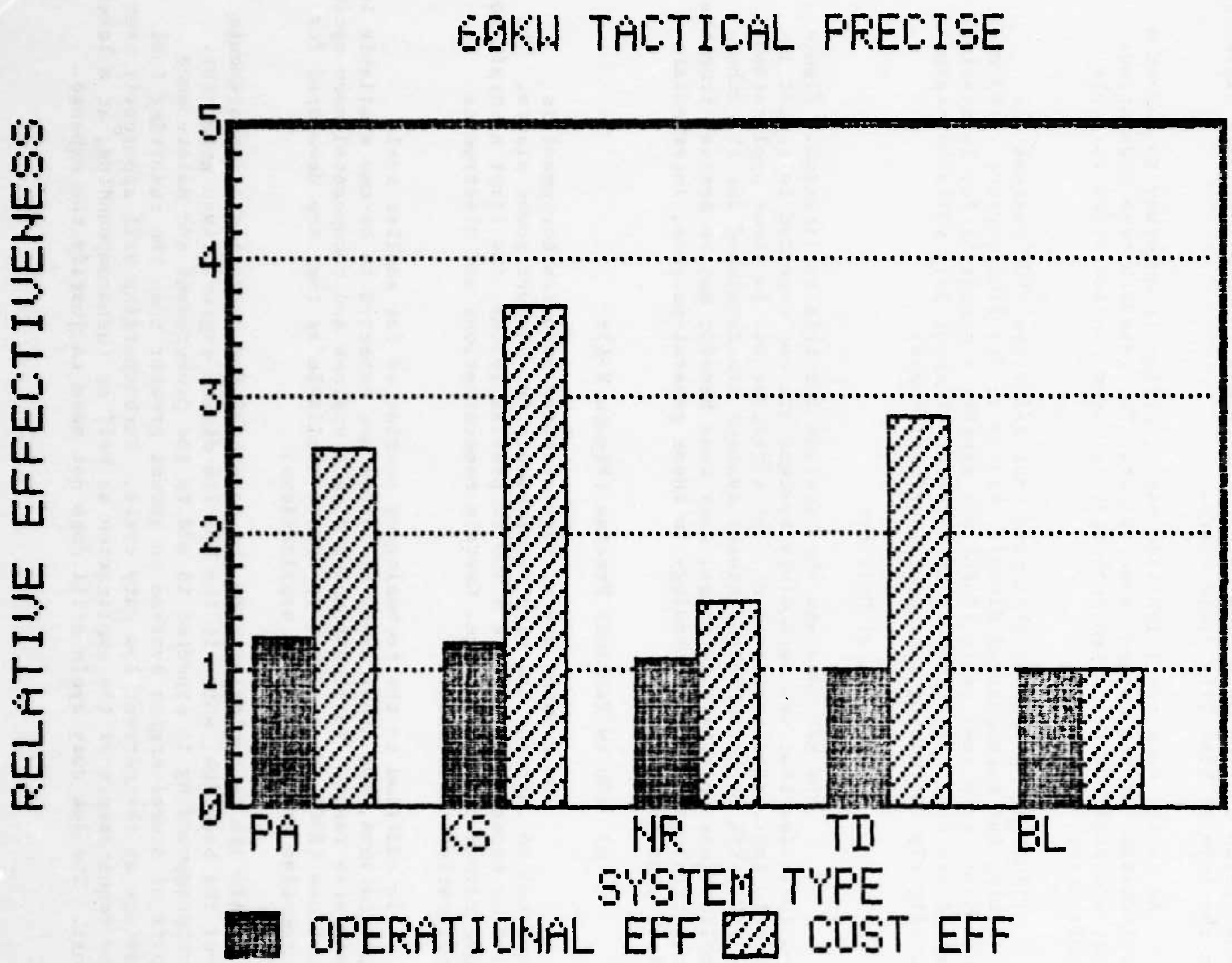

FIGURE V-4: 60KW TACTICAL PRECISE

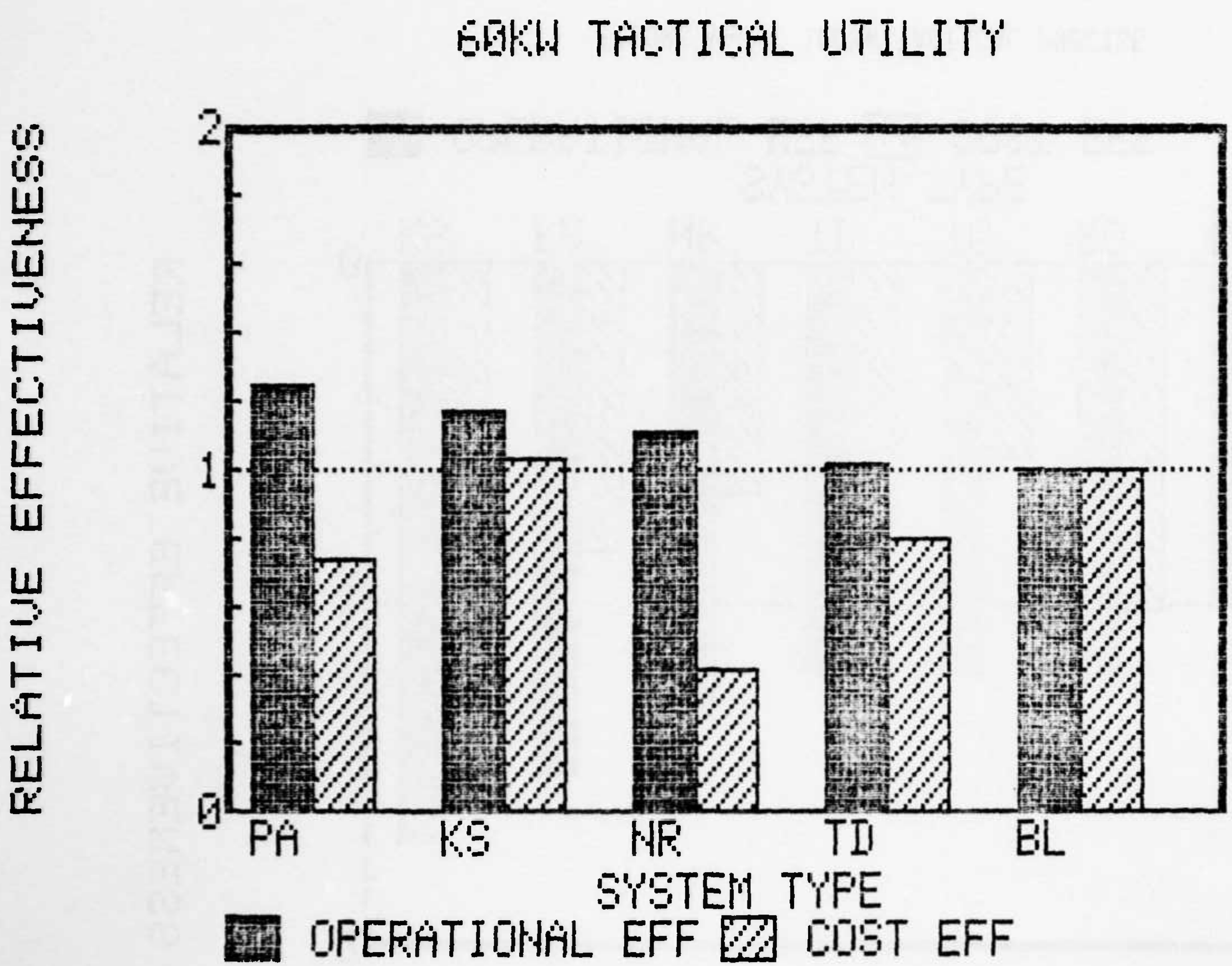

FIGURE V-5: 60KW TACTICAL UTILITY

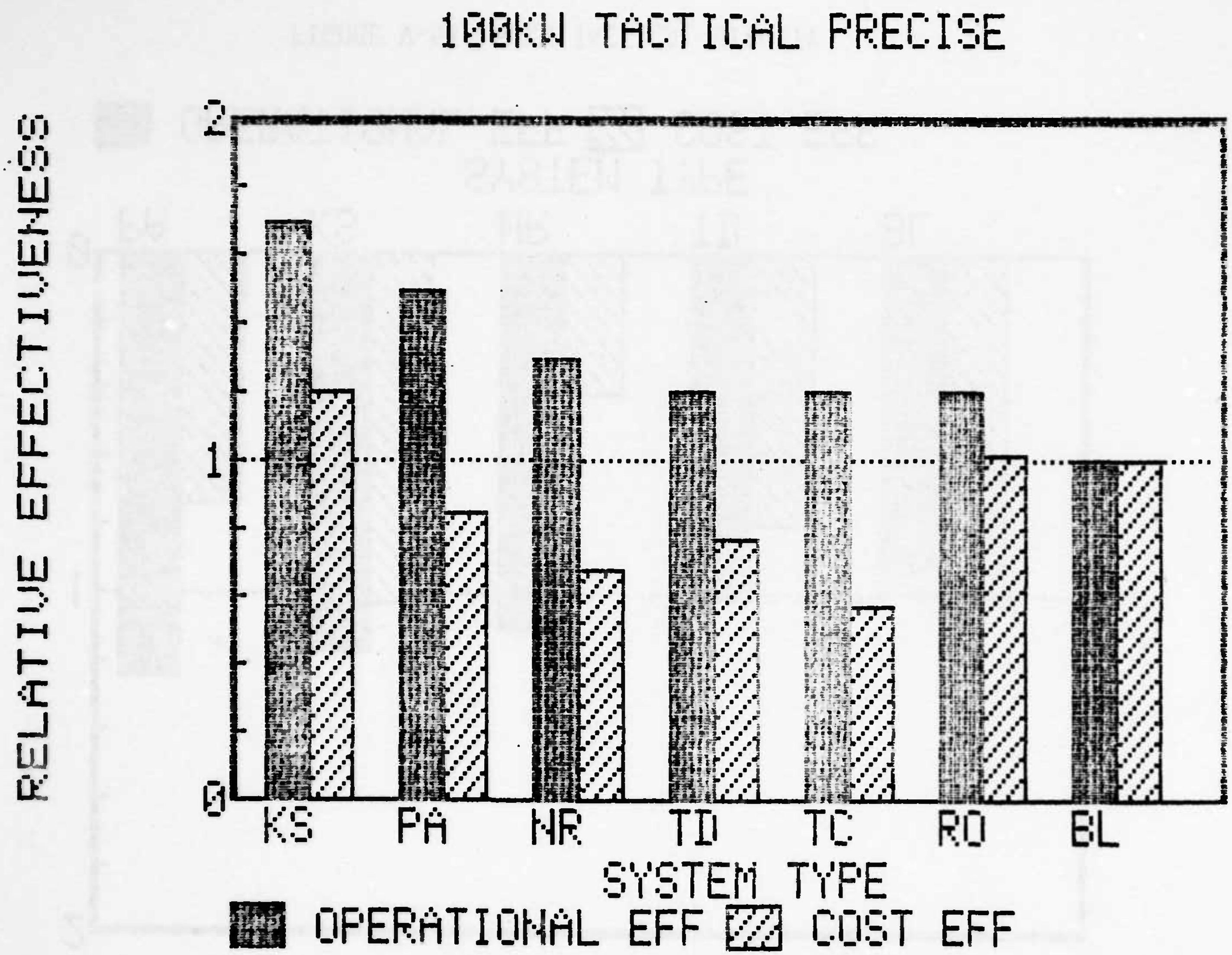

FIGURE V-6: 100KW TACTICAL PRECISE

The best opportunities for improvement are KSE, PAFC and ROC technologies. KSE systems have the advantage over fuel cells due to their projected longer lifetime, higher mobility, and shorter start-up time. Fuel cells are expected to be simpler to use and somewhat more fuel efficient. With in-stack reforming, they may be smaller and lighter weight.

The efficiency penalties paid by smaller turbines decrease in the 100 kW sizes. Regeneration promises additional increases in fuel efficiency which are substantial enough to impact on system cost even at low duty cycles. Regenerative cycles are more sensitive to load, and pay a high efficicency penalty for turn down and load following, however, resulting in a net decrease in operational effectiveness.

Kinematic Stirling engines and regenerative open cycle gas turbines seem to offer the best overall potential for enhanced effectiveness in 100 kW precise applications. When the limits of precision in the study are taken into account, phosporic acid fuel cells must be considered to be an equally attractive alternative. Turbocharged and turbocompound diesels and non-regenerative open cycle turbines also have a potential to improve upon the baseline system.

f) 100 kW Tactical Utility (Figure V-7):

The MEP 007 series diesel engine generator is the baseline system for these applications. The analysis shows it to be an operationally and cost effective power plant for these general applications. Only kinematic Stirling systems have a generally good potential to improve upon the baseline in a cost effective manner. Regenerated gas turbines have a smaller, but real potential to improve upon the baseline within the limits of precision of the study.

This application area does not in itself seem to justify a USAF R&D program. However, systems which are applicable to tactical utility applications could be a byproduct of the development of tactical precise power plants for flightline and/or other electronic systems support.

g) 250 kW Tactical Utility (Figure V-8):

Kinematic Stirling engines offer the best potential for increasing operational effectiveness at a competitive cost for these applications. An analysis of the elements of the life cycle cost equation indicates that the new technology systems all offer reduced fuel costs through increased fuel efficiency, but with projected purchase and maintenance costs several times that of the baseline. When duty cycles are as low as typical MEP applications, the reduction in fuel costs does not economically justify the higher purchase price of most competing technologies.

The logistical impact of increased fuel efficiency is incorporated into the measure of operational effectiveness, however. Increased

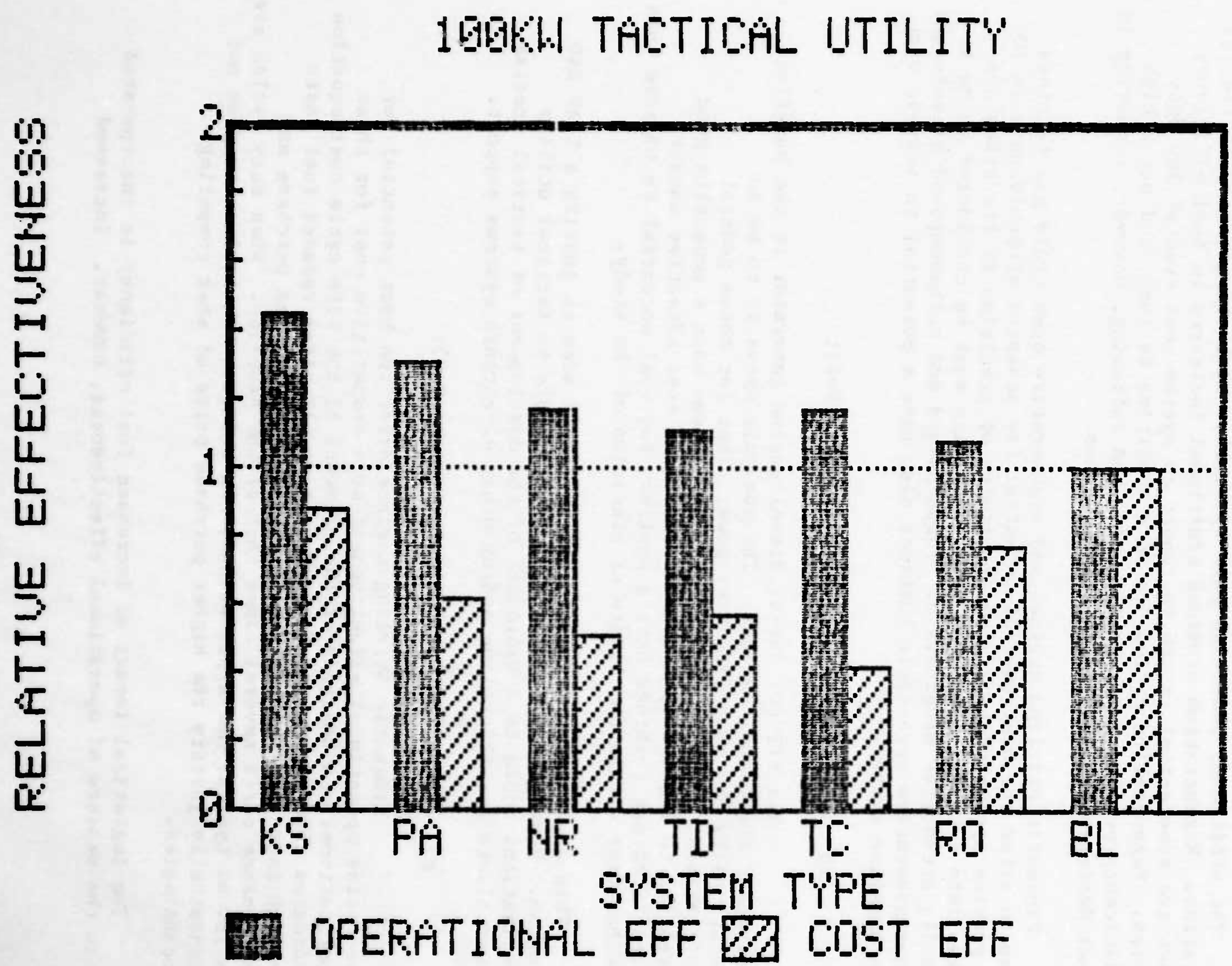

FIGURE V-7: 100KW TACTICAL UTILITY

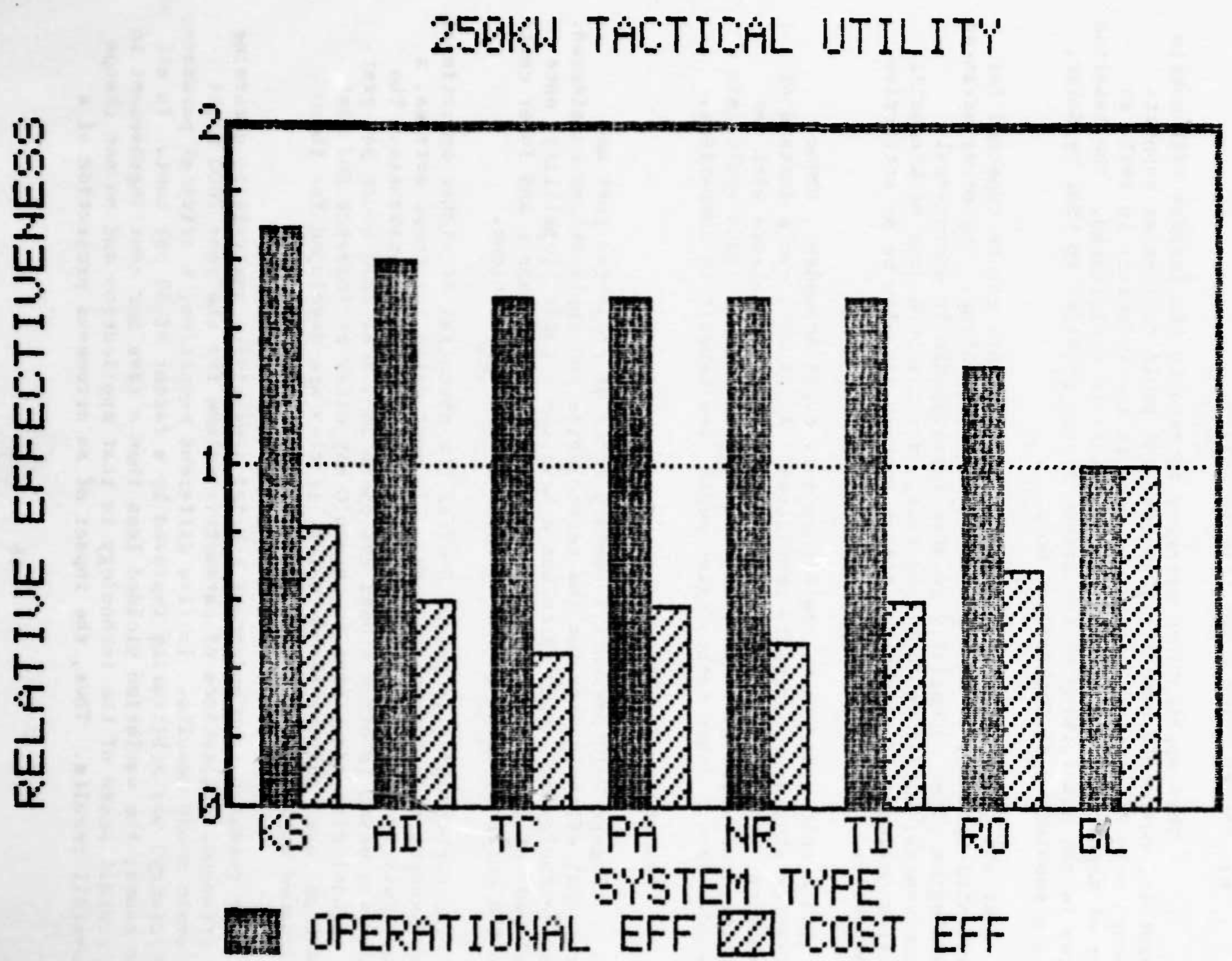

FIGURE V-8: 250KW TACTICAL UTILITY

mobility, operability, and reduced noise are among the other anticipated factors which kinematic Stirling engines offer in comparison with the baseline. For 250 kW tactical utility applications, USAF will have to consider the relative value of increased operational effectiveness in making technology selections.

h) 750 kW Prime Power (Figure V-9):

This applications category represents the largest USAF mobile generators, currently used for bare base and rapid deployment support. Although only 26 of these generators were in the inventory in 1982, an order of magnitude expansion of the inventory is anticipated. The baseline system is the gas turbine engine driven system provided to USAF by Solar, Inc., a subsidiary of Caterpillar Corp.

Cost and operational effectiveness improvements can be expected for regenerated tubines, as an improvement on the baseline. The other advanced technologies offer potentially greater improvements in operational effectiveness, but at an increased cost, except in the case of kinematic Stirling engines. Turbocharged diesel engines may also be an attractive alternative.

Since cost projections are highly duty cycle dependent, these statistics should be carefully considered. A 25% duty cycle instead of one-eighth, would give turbocharged diesels cost equivalence with the baseline, and would give KSE systems a 1.16 advantage. ROCs would gain a 1.19 advantage. Other technologies would also benefit in comparison.

4) Summary of Results

Figure V-10 presents a summary table of projected cost and operational effectiveness for the technologies and applications considered. Those technologies listed in column A have the highest probability, once developed, of providing MEP systems with better performance and lower costs than the current system in the designated USAF applications.

The technologies in column B offer the potential of higher operational effectiveness at a competitive cost. In most cases for these entries, a longer duty cycle would be the key to enhanced cost effectiveness. The break even point is often around 25% operation, i.e. 2200 hours per year. The technologies identified in column C may offer performance and cost advantages over current technologies, if they are developed for the designated application.

The research team undertook a brief sensitivity analysis to determine how erroneous projections of parametric values for the year 2000 might influence study results. In five different scenarios, a critical parameter (deficiency) was arbitrarily improved by a factor of 50 per cent. In all five cases, the variation yielded less than a five per cent improvement in the overall score of the technology in that application and no net change in overall results. Thus, the impact of an erroneous projection of a

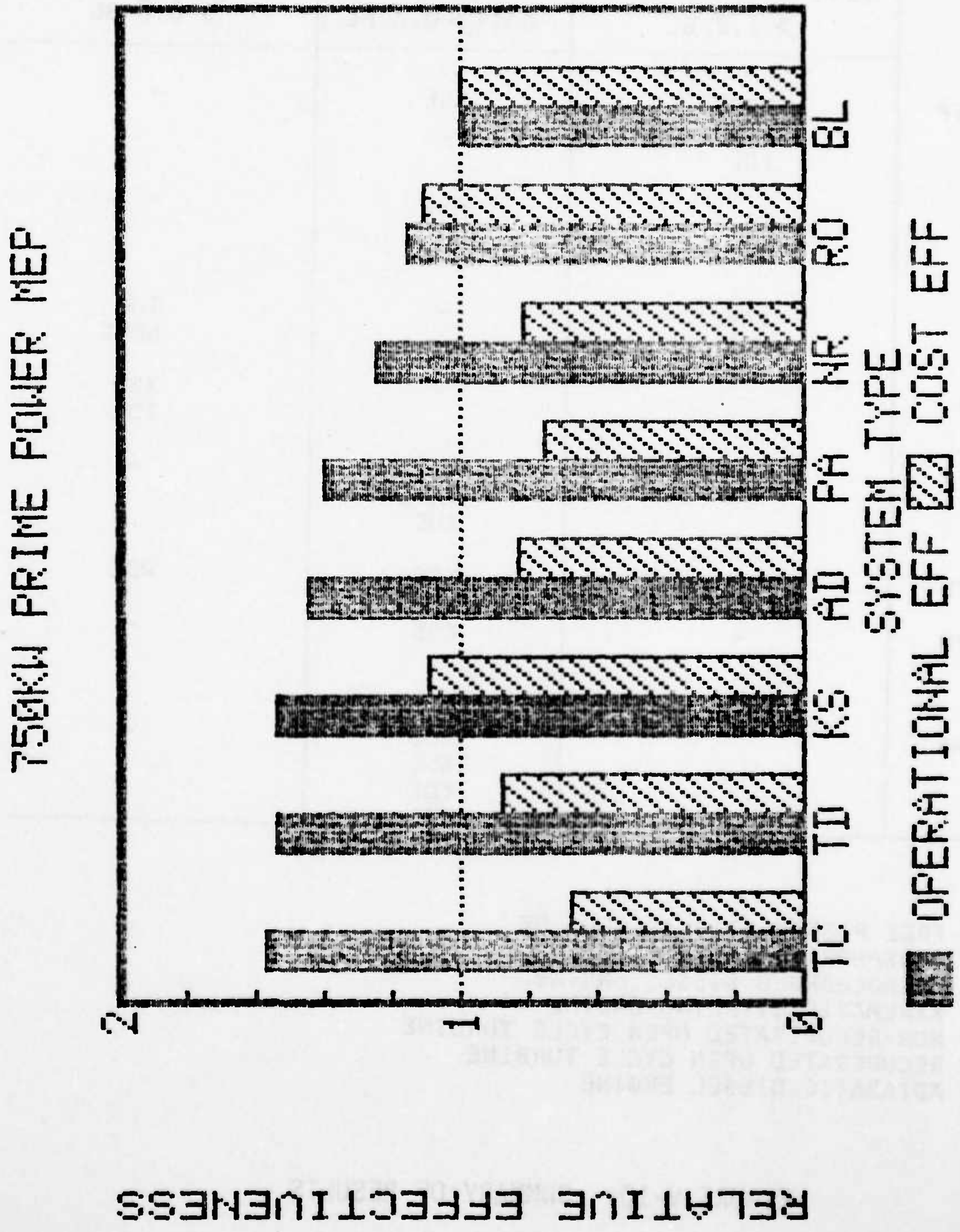

FIGURE V-9: 750KW PRIME POWER MEP

	A COST & PERFORMANCE $>$ 1.2 BL	B PERF $>$ 1.2 BL COST $>$ 0.8 BL	C COST & PERFORMANCE $>$ 0.8 BL
5KW TU/TP	FPSE PAFC TDE	KSE	-
60KW FL	-	KSE PAFC TDE	-
60KW TP	PAFC KSE	-	TDE NROC
60KW TU	-	-	KSE TDE
100KW TP	KSE	ROC PAFC TDE	-
100KW TU	-	KSE	ROC
250KW TU	-	KSE	-
750KW PP		ROC KSE TDE ADE	-

FPSE = FREE PISTON STIRLING ENGINE
PAFC = PHOSPHORIC ACID FUEL CELL
TDE = TURBOCHARGED DIESEL ENGINE
KSE = KINEMATIC STIRLING ENGINE
NROC = NON-RECUPERATED OPEN CYCLE TURBINE
ROC = RECUPERATED OPEN CYCLE TURBINE
ADE = ADIABATIC DIESEL ENGINE

FIGURE V-10: SUMMARY OF RESULTS

critical variable (~5%) was judged to be far less than the generally estimated precision of the analysis (25%).

Several general conclusions may be drawn at this point. Free piston Stirling engines have the highest potential for USAF application in small sizes, but are limited to small power systems. Phosphoric acid fuel cells have a high potential for enhancing effectiveness in small and mid-sized power plants. Kinematic Stirling engines have potential applicability to all USAF MEP applications, and are the system of choice for mid-sized applications. Regenerative turbine engines are good choices for large systems, and should be considered for systems larger than 250 kW. Small diesel engines will benefit from turbocharging, but larger systems will not repay the expense for low duty cycle applications.

Finally, it is valuable to note that the greatest opportunity for enhanced performance through new technology development is in those applications which are most mission essential, namely the tactical precise avionics and electronics support area.

VI. System Deficiencies and R&D Potential

A. Approach

Each of the consultant and subcontractor members of the research team was asked to consider the R&D requirements of the advanced technology systems, based upon the parametric operational effectiveness analysis. The team members were asked to consider deficiencies from two different perspectives:

1) What R&D is necessary to move from the 1982 state of the art to achieve the parametric values which were used in the analysis? This perspective was chosen to provide insight as to the minimum R&D required to achieve fielded systems in USAF applications meeting the operational and cost effectiveness projections presented in section V above and in Appendices D & E.

2) Where might additional, high risk R&D be undertaken to accelerate the achievement of those values or to increase systems' effectiveness beyond those values? This perspective was chosen to help determine how USAF might accelerate the development of technologies should it be advisable or necessary to meet USAF mission objectives.

Team members were directed to consider the overall objective of this task to be the detection of high pay-off areas for incremental R & D funding by AFWAL. They were asked to consider research currently in progress, as well as the specific problem areas for their technologies and applications of interest. As a result of these considerations, team members were asked to develop statements of research need, to include a set of ranked research priorities describing the deficiencies which research was to overcome, and the rationale for potential R&D exploitation.

Team members were instructed to develop priorities, at this point, as though they were unconstrained by cost considerations. Because of the diversity of technology areas and the R & D programmatic expertise of the team members, no constraints were placed on content or format other than those mentioned above. The reports of the team members may be assumed to reflect the advantages and the biases of their corporate experiences and perspectives.

The project manager was responsible for integration of the team members' reports, and for selection of high pay-off areas for R&D. Integration consisted of the consideration of the content and conclusions of the technical experts, and comparison of the R&D opportunities which were identified in the technical reports with the relative potential impact of R & D as indicated by the MADM analyses.

B. Results

Figure VI-1 presents a summary of the technical subcontractors' recommendations for research and development to overcome system deficiencies. For the purposes of these recommendations, deficiencies mean the gaps between the current state of the art and year 2000 parameters as

Technology	Priority	Recommended Area of R&D
Stirling Engine (free piston and kinematic)	First	Ceramic engine component development.
	Second	Kinematic engine generator set development.
	Third	Engine upsizing for free piston and kinematic units.
Phosphoric Acid Fuel Cells	First	Efficient turbo-charging equipment.
	Second	Low-cost, corrosion resistant plate development.
	Third	CO tolerant anode electrocatalysts.
Gas Turbine	First	Water cooling.
	Second	Ceramic component development.
	Third	Preventative diagnostic monitoring and retirement for cause.
Diesel	First	Process development to attach ceramic parts to metal parts.
	Second	Ceramic reciprocating parts and ceramic Adiabatic engine component development.
	Third	Alcohol fuel for diesels.

Figure VI-1:

Summary of R&D Required to Meet ATES Projected Performance contained in the modified ATES. In general, this means relatively low risk R & D which is likely to achieve its objectives within the time period and at a reasonable cost.

Figure VI-2 presents a summary of the research team's recommendations for research and development to exceed the values of the modified ATES parameters or to accelerate the attainment of those parameters. For the purpose of these recommendations, deficiencies mean the difference between the modified ATES parameters and the conceivable state-of-the-art, which would result in improved performance beyond the results of the MADM analysis. In other words, Figure VI-2 answers the question, "What can be done to change a non-favored technology into a favored one?"

The research team's individual reports on research and development requirements for the technologies of interest provide a parametric consideration of deficiencies which underlie the summary recommendations in Figures VI-1 and VI-2. They include an identification of the general research thrusts currently underway. They also include an identification of additional R & D recommendations, of lower priority than that in the summary table. These reports are included as Appendix F to this report.

Based upon the identification of R & D opportunities as presented in Figures VI-1 and VI-2, and upon a consideration of the results of the operational and cost effectiveness analysis as summarized in Figure V-10, the research team recommended eleven areas for R & D emphasis. These recommendations were presented to the project engineer for review prior to the development of cost estimates for the recommended projects. Each of those recommendations is briefly discussed here:

1) Free Piston Stirling Engine: The principal need is for proof of concept through fabrication of a five kilowatt prototype and larger, followed through by field testing of the prototype. The largest system known to be currently under advanced development is in the 3 kW range. The development of larger prototypes is several years behind. In order to achieve a fielded 5 kW system for USAF utilization by 1990, work must be undertaken to develop and field a 5 kW prototype.

In addition to the necessity of gaining general experience with the technology, there is an opportunity to maximize FPSE system performance and lifetime through the development of ceramic heater heads. These two programs, taken together, should contribute to the achievement of a highly effective, low cost power plant for small USAF applications.

2) Phosphoric Acid Fuel Cell: A principal need is the development of turbocharging equipment, for small fuel cells. This is critical to achieving system size and weight objectives as well as for high efficiency of fuel conversion.

Potentially even more effective will be the development of in situ reforming. Much of the weight and volume of PAFC fuel cells is associated with the external reformer, which converts the primary fuel into hydrogen,

Technology	Priority	Recommended Area of R&D
Stirling Engine (free piston and kinematic)	First	Expanded multifuel operation.
	Second	Accelerate ceramic activities to achieve even higher efficiency.
	Third	Accelerate upsizing development.
Phosphoric Acid Fuel Cells	First	Catalyst research.
	Second	Alternate support development with improved corrosion resistance.
	Third	Integration of reforming catalyst into fuel cell stack.
Gas Turbine	First	Composites and ceramic materials.
	Second	Materials, cooling, and monitoring systems.
	Third	Computer-aided engineering design.
Solid Polymer Fuel Cell (long term)	First	Prototype development and testing under actual conditions.
	Second	Low cost, polymeric membrane development.
	Third	Reduction in catalyst loading and electrode structure development.

Figure VI-2:

Summary of Advanced R&D Required to Surpass ATES Projected Performance

which is the reactive agent. For example, Giner Inc. reports estimates that a 20 kW system could be reduced 50% in volume and 30% in weight through in-stack reforming.

Sulfur is a ubiquitous contaminant in fossil fuels. It is one which poisons, or degrades the performance of fuel cell electrocatalysts and reforming catalysts. Maintaining catalytic components is a potential major expense and a maintenance burden for these systems. Methods which are currently employed to remove hydrogen sulfide upstream of the reformer or fuel cell are expensive and add to system volume and weight. The development of catalysts which are not sensitive to sulfur poisoning would thus contribute simultaneously to a variety of parametric improvements.

After system size and weight considerations, one area of concern for this technology is that of slow start-up times. A major factor behind this characteristic is the poisoning of anode electrocatalysts by carbon monoxide (CO). To minimize CO poisoning, PAFC systems are operated at temperatures up to 350 degrees F. Bringing the system up to operating temperature is a time consuming process. Moreover, CO presence in the fuel cell is minimized by the use of a low temperature shift reactor in the reformer stream, reducing CO concentration from several per cent ot less than one percent. The development of CO tolerant anode electrocatalysts would thus reduce plant size and weight through the elimination of this subsystem.

Finally, there is an advanced research opportunity to simultaneously attack the problems of plant size, weight, efficiency and start up time. Such a systems approach would concentrate upon development of alternative electrolyte fuel cells. As a replacement for phosphoric acid, aqueous potassium carbonate and triflouromethane sulfonic acid (TFMSA) have demonstrated certain beneficial qualities. This high risk, high payoff approach would include not only electrolyte research and characterization, but would also require a significant effort in redesigning electrodes and other components as well.

3) Kinematic Stirling engine: Ceramic component development programs will be required to enable Stirling engines to achieve the levels of efficiency and system lifetimes predicted for the 2000 time frame. In essence, this is supportive of higher temperature operation than can be achieved with metal components. Several projects are underway in the general area of ceramic components. For the most part, these programs are oriented to existing engine designs and are being pursued for possible retrofit. In addition, numerous ceramic component development projects are underway in other engine areas, including diesel and gas turbine engines.

The research team recommends that advantage be taken of research in these areas, by undertaking a ceramic KSE development project. This development effort would seek to take advantage of the performance potential of ceramic components wherever possible, including preheater, heater heads, piston domes, thermal dams, bearings and regenerators.

Stirling engines are currently available only on a limited basis. Current development activities are limited to systems smaller than about 100 kW. Most research centers on automotive applications, and additional work must be done to adapt automotive engines to electric generator applications.

The research team therefore recommends R & D programs to match a KSE engine to a MEP-type generator, and to field test such a system under USAF duty cycle requirements. The results of such experience would result in the identification of design modifications for improved operational effectiveness as well as reliability, availability and maintainability.

4) Adiabatic, turbocharged and turbocompounded diesel engines: Except for the smallest engine generator sizes, the use of advanced diesel engine generators does not seem justified for USAF MEP applications because of the low duty cycles which are common for these systems. Other technology candidates, i.e. Stirling cycle engines and phosphoric acid fuel cells also have a high potential to meet small power system needs. Except for the free piston Stirling engine, these technologies have applicability to a broad number of sizes and missions, so that R&D in these areas can be expected to have pay-off in a broader number of USAF applications.

Most important, is the fact that the automotive industry in Europe, Japan, and the U.S. is pursuing advanced diesel engine research at a level which is disproportionate to USAF's power to add or detract. To the extent that advanced diesel engine technologies become feasible to USAF applications, they can reasonably be expected to become available through commercial channels, without direct USAF support of R&D. For these reasons, the research team recommends that USAF technology development programs concentrate on the other technology options.

5) Gas turbine engines: Closed cycle gas turbine engines are not projected to be available in MEP system sizes during the period of interest. Recuperated and non-recuperated open cycle systems show a potential for increased operational effectiveness only in the larger system sizes (750 kW and 250 kW). Non recuperated systems are those which are currently used by USAF for support of bare base operations. The increase in operational effectiveness and modest cost improvement for these systems, like the diesel technologies which are also a standard commercial product, may be expected to result from ongoing R&D in the commercial sector.

Recuperation of exhaust heat, on the other hand, seems to offer reasonable improvements in operational effectiveness and in cost effectiveness at the 750 kW size level, even at low rates of utilization. Research in regeneration is underway, but the large MEP application is unique to the military services. Therefore the research team recommends that USAF consider R&D leading to a mobile 750 kW regenerative open cycle gas turbine generator.

VII. Nature and Costs of R&D to Overcome Deficiencies

The following are the summaries developed for the R&D programs, identified as desirable in section VI, above. Program descriptions were provided by the technical subcontractors. Cost estimates have been rounded to two significant digits, as appropriate for estimates or projections of this sort. Standard overhead and G&A values of 125% and 25% were assumed for the sake of common comparison. No profit or fee was included in the cost estimates.

A. Free Piston Stirling Engine(FPSE): Develop and provide field test support for a 5 kW prototype MEP generating system:

Estimated Cost	Estimated Level of Effort	Estimated Length of the Developmental Work
$2,500,000	17 Person Yrs	28 Months

Objective:

To deliver seven stand-alone, 5 kW Free-Piston Stirling Engine/Generator Sets for prototype field evaluation.

Specifications:

- 5 kW electric power at .8 lagging power factor
- 60 Hz 120 VAC single phase
- 23% overall efficiency
- Military transient control requirements
- 5000 hours before overhaul
- 750 hours mean time between failure
- Multifuel (diesel, DFA, JP-4, JP-5, combat gasoline)
- Silent at 100 meters
- 800 lbs. and 15 $ft.^3$

Approach:

The recommended program would utilize the experience gained during field tests of the 3 kW Advanced Development Model (ADM) which was developed for MERADCOM. The program would utilize the same design approach and engine configuration as the ADM; but, components will be upgraded to meet the 5 kW power requirement. Component development would be directed at:

- Improving reliability
- System auxiliaries
- Control system complexity
- Overall package configuration
- Weight reduction

The existing 3 kW FPSE/generator sets would be used to support early component development tasks.

Major Tasks:

1.0 Power module design
2.0 Component development
3.0 System design
4.0 Fabrication
5.0 Development
6.0 Fabrication of field marks
7.0 Acceptance tests
8.0 Delivery
9.0 Field test support

Estimated Program Costs: ($ thousands)

Total direct labor costs	$500
Overhead costs (@125%)	625
Material	850
Other direct costs	33
General & Administration (@25%)	500
TOTAL	**$2,500**

B. FPSE: Develop ceramic heater head to increase efficiency and system life:

Estimated Cost	Estimated Level of Effort	Estimated Length of the Developmental Work
$790,000	5 Person Yrs.	30 Months

Objective:

To develop a ceramic heater head for a FPSE with the capability of operating for a relatively long life (10,000 hrs) at high input temperatures with the goal of improving engine performance by 10 to 15% over all metallic FPSE's.

Specifications:

- Helium working fluid
- Heat transfer rate of 20 KBTU/H
- Operating temperature of 1000°C wall and no less than 900°C helium
- 10,000 hour life

• >60 atmosphere pressure

Approach:

The recommended program would be divided into two phases. The Phase I effort would be a proof of concept project, relying on rig tests to verify operational capability. Twelve heater heads would be fabricated in order to obtain a minimum statistical data sample.

The tests to be performed on the experimental heater heads would include: proof test, burst test, static test, and thermal shock test. Development items would include attachment techniques as well as fabrication processes.

The second phase of the program would involve design modifications to enable testing of at least three heater heads with engine systems to monitor the effects on engine performance and operation.

Major Tasks:

Phase I	1.0	Materials selection
	2.0	Analysis and design
	3.0	Fabrication
	4.0	Rig test development
	5.0	Test
Phase II	6.0	Design modification
	7.0	Fabrication
	8.0	Engine integration
	9.0	Performance test

Estimated Progam Costs: ($ thousands)

Total direct labor costs	$170
Overhead costs (@125%)	210
Material costs	10
Other direct costs	235
General and Administrative (@ 25%)	160
TOTAL	**$790**

C. Phosphoric Acid Fuel Cell (PAFC): Develop turbocharging equipment for small fuel cells:

Estimated Cost	Estimated Level of Effort	Estimated Length of the Developmental Work
$2,400,000	**24 Person Yrs**	**24 Months**

Objective:

To develop small, efficient turbocharging equipment for use with PAFC power plants sized for mobile applications.

Background:

A significant improvement in the performance of large (e.g., 4.8MW) PAFC's has been the development of pressurized power plants with the use of turbochargers. This feature has not been exploited for small PAFC power plants. Pressurization has lead to power plants of improved efficiency, reduced the size and cost of the reformer, and enhanced water recovery.

Approach:

The weight, volume and cost characteristics of small PAFC power plants for mobile applications may be improved by pressurization. A cost and energy efficient approach to achieve this goal is to utilize the cathode and anode exhaust gas to generate a high temperature gas stream. The waste energy in this stream is then recovered by passing it through a turbo-compressor which pressurizes the reactants.

Major Tasks:

1.0 Evaluate the feasibility of a small turbocharger for a PAFC
2.0 Develop an envelope of operating conditions and power (size) for pressurization by a turbocharger
3.0 Development of the small turbocharger
4.0 Integration of the turbocharger with a PAFC
5.0 Shakedown and endurance testing

Estimated Program Costs: ($ thousands)

Total direct labor costs	$ 730
Overhead costs (@ 125%)	910
Material costs	250
General and Administrative (@ 25%)	470
TOTAL	**$2,400**

D. PAFC: Development of an "in stack" reformer:

Estimated Cost	Estimated Level of Effort	Estimated Length of the Development Work
$5,800,000	63 Person Yrs	36 Months

Objective:

To reduce the weight and volume of PAFCs by "in-situ" reforming.

Background:

Much of the weight and volume of PAFC power plants are associated with the reformer. For a 20 kW PAFC, "in stack" reforming would reduce the system volume and estimated weight 50% and 30%, respectively. The "in-situ" approach outlined below should effect even further reductions in volume and weight.

Approach:

In the "in-situ" approach, the reforming catalyst is included in the fuel cell anode cavity. This approach provides for a thermal integration of the endothermic reforming reaction with the exothermic fuel cell reaction, thereby increasing the thermal efficiency of the system and eliminating the fuel cell coolers. Furthermore, since the anode (where hydrogen is consumed) is close to the reformer, the continuous removal of hydrogen from the reaction zone shifts the reforming reaction in such a way that the amount of CO (an anode poison) produced is minimized. The approach will be to develop reforming catalysts which could be incorporated into bifunctional anode structures. These bifunctional anode structures would then serve the dual function of reforming and hydrogen oxidation.

Major Tasks:

1.0 Candidate catalyst selection
2.0 Preparation and characterization of catalysts
3.0 Evaluation of reforming characteristics
4.0 Incorporate reforming catalysts into bifunctional anode structures
5.0 Long term stability evaluation of "in situ" reforming concept

Estimated Program Costs ($ thousands):

Total direct labor costs		$1,800
Overhead costs	(@ 125%)	2,300
Material costs		560
General & Administrative	(@ 25%)	1,200
TOTAL		**$5,800**

E. PAFC: Develop an H_2S insensitive reforming catalyst:

Estimated Cost	Estimated Level of Effort	Estimated Length of the Developmental Work
$3,600,000	39 Person Yrs	36 Months

Objective:

To develop reforming catalysts which are not adversely affected by H_2S.

Background:

Sulfur is a ubiquitous contaiminant in all fossil fuels. H_2S poisons the reforming catalysts as well as the fuel cell electrocatalysts. Consequently, methods to remove H_2S upstream of the reformer or fuel cell must be employed. These methods are expensive and add to the power plant weight and volume. In addition to added expense, the added weight and volume are particularly critical considerations for small PAFC power plants to be used in mobile applications.

Approach:

The recommended program is directed toward the development of catalysts for reforming (and for the fuel cell electrodes) which are insensitive to the H_2S present in the fuel stream.

Major Tasks:

1.0 Identification of promising catalyst systems
2.0 Preparation and characterization of the most attractive candidates as H_2S tolerant anode electrocatalysts
3.0 Evaluation of reforming characteristics
4.0 Evaluation of hydrogen oxidation characteristics
5.0 Evaluation of the effect of H_2S on the reforming reaction
6.0 Evaluation of the effect of H_2S on the hydrogen oxidation reaction
7.0 Integration of the H_2S insensitive reforming catalyst with a PAFC utilizing an H_2S insensitive anode electrocatalyst
8.0 Long term stability evaluation of an integrated system under H_2S contamination

Estimated Program Costs ($ thousands):

Total direct labor costs	$1,100
Overhead costs	1,400
Material costs	350
General & Administrative (@ 25%)	710
TOTAL	**$3,600**

F. PAFC: Development of CO tolerant anode electrocatalysts:

Estimated Cost	Estimated Level of Effort	Estimated Length of the Development Work
$2,300,000	29 Person Yrs	18 Months

Objective:

To develop CO tolerant anode electrocatalysts for PAFC's.

Background:

In order to minimize CO poisoning of the anode electrocatalysts, PAFC power plants use low temperature shift reactors to reduce the CO level in the reformer stream from several percent to less than one percent prior to entry into the fuel cell. The development of CO tolerant anode electrocatalysts would elminate the need for the shift reactor and thus reduce the power plant weight, volume, and complexity. An additional concern for mobile power plant operation is the lengthy start-up times required for the PAFC to reach an operating temperature when the CO poisoning problem is tolerable.

Approach:

The recommended program is designed to reduce PAFC weight, volume, and start-up time by the development of a CO tolerant anode electrocatalyst.

Major Tasks:

1.0 Identification of promising catalyst systems
2.0 Preparation and characterization of selected catalysts
3.0 Evaluation of hydrogen oxidation activity
4.0 Evaluation of tolerance to CO in the hydrogen fuel stream
5.0 Long term testing of CO tolerance anode electrocatalysts in complete fuel cells

Estimated Program Costs ($ thousands):

Total direct labor costs		$ 730
Overhead costs		910
Material costs		225
General & Administrative	(@ 25%)	470
TOTAL		**$2,300**

G. PAFC: Development of an alternative acid electrolyte:

Estimated Cost	Estimated Level of Effort	Estimated Length of the Developmental Work
$9,200,000	100 Person Yrs	120 Months

Objective:

To develop an electrolyte for use in an acid fuel cell with better performance than phosphoric acid systems.

Background:

The oxygen reduction activity of low surface area, smooth platinum in trifluoromethane sulfonic acid (TFMSA) is better than in phosphoric acid. However, several systems considerations (e.g., vapor pressure, Teflon wetting, conductivity) render TFMSA incompatible with the components developed for PAFC.

Approach:

The approach of this recommended program is to develop alternate electrolytes with beneficial systems characteristics and enhanced platinum oxygen reduction activity in TFMSA. In order for alternate electrolyte fuel cells to become a reality, a significant effort in redesigning the gas diffusion electrode structure, as well as their components, is required.

Major Tasks:

1.0 Identification of alternate electrolytes with favorable systems charactertistics as well as with similar oxygen reduction behavior as TFMSA
2.0 Synthesis and characterization of candidates
3.0 Characterization of physical properties important for fuel cell power plants (e.g., vapor pressure, stability, conductivity, Teflon contact angle)
4.0 Mechanistic study of oxygen reduction on platinum in the candidate alternate electrolytes
5.0 Redesign of gas diffusion electrode and other components for compatibility with alternate electrolyte fuel cell
6.0 Characterization of complete fuel cell performance and stability

Estimated Program Costs ($ thousands):

Total direct labor costs	$2,900
Overhead costs (@ 125%)	3,600
Material costs	850
General & Administrative (@ 25%)	1,800
TOTAL	**$9,200**

H. Kinematic Stirling Engine (KSE): Development of ceramic component engine:

Estimated Cost	Estimated Level of Effort	Estimated Length of the Development Work
$23,000,000	132 Person Yrs	78 Months

Objective:

To design and develop a kinematic Stirling engine which utilizes ceramic components to achieve engine efficiencies which are significantly greater than efficiencies available with metallic designs.

Approach:

This recommended program recognizes the fact that, currently, there are a number of ceramic Stirling engine projects being funded. The ongoing projects are constrained to existing engine design, whereby ceramic components are being pursued for possible retrofit. The proposed program recommends starting with a "clean", unconstrained design which can be tailored to take advantage of the performance potential of ceramic components, wherever appropriate.

The recommended program consists of three phases. Phase I would address a conceptual design effort to establish a kinematic Stirling engine which utilizes ceramic materials, wherever potential performance benefits are evident. Some example uses of ceramic elements that would be considered include: preheater, heater heads, piston domes, thermal dams to reduce conduction losses, ceramic bearings, and ceramic regenerators. The design effort would be heavily supported by analytical activity to verify the efficiency gains anticipated. The output of this phase would be a conceptual design and layout, an analytical assessment of engine performance, and an identification of required component development.

Phase II would consist of a 14 month effort to verify ceramic component feasibility. The project would rely heavily on rig tests to verify operational capability. A sufficient number of parts would be fabricated for each component to obtain a good statistical sampling. Additionally, fabrication techniques would be developed for each component.

Phase III would involve design modifications to the conceptual design based on the knowledge base established during Phase II. The design would be detailed and three engines would be fabricated. The ceramic engines would be performance tested in order to verify efficiency improvements of the ceramic components.

Major Tasks:

Phase I (12 Months)

1.0 Design
2.0 Analysis
3.0 Component development planning

Phase II (14 Months)

4.0 Analysis design
5.0 Fabrication process development
6.0 Fabrication
7.0 Rig test

Phase III (52 Months)

8.0 Design modification
9.0 Fabrication
10.0 Component development
11.0 Engine assembly and checkout
12.0 Performance test

Estimated Program Costs ($ thousands):

Phase I

Direct labor costs	$ 35
Overhead costs (@ 125%)	44
Other direct costs	62
General & Administrative (@ 25%)	35
TOTAL	**$ 180**

Phase II

Direct labor costs	$ 280
Overhead costs (@ 125%)	350
Material costs	1,800
Other direct costs	18
General & Administrative (@ 25%)	610
TOTAL	**$3,100**

Phase III

Direct labor costs		$3,800
Overhead costs (@ 125%)		$4,800
Material costs		$5,000
Other direct costs		$2,200
General & Administrative	(@ 25%)	$4,000
TOTAL		**$20,000**
GRAND TOTAL		**$23,000**

I. KSE: Development and Field Testing of a matched kinematic Stirling engine and generator:

Estimated Cost	Estimated Level of Effort	Estimated Length of the Development Work
$2,100,000	7.0 Person Years	36 Months

1) Phase I. Development

Objective:

To demonstrate that a Kinematic Stirling engine can be matched to a generator.

Approach:

The 60 kW kinematic Stirling engine being developed as part of the Automotive Stirling Engine (ASE) Program, through NASA Lewis, would be well-suited for integration with either a 15 kW or 30 kW generator set. The auxiliaries, control system, and packaging would have to be customized to a specific generator configuration and duty. The demonstration could be accomplished through system tests and evaluation of the overall system performance and function. The outlined generator matching development program is recommended to be separated and completed in two phases.

In the first phase, an existing ASE program engine would be coupled to an "off-the-shelf" generator and operated in both steady-state and transient conditions using a specially designed digital engine control. This control would maintain the engine at constant speed under varying load conditions, unlike the existing control which maintains a torque level. Testing would include response time, load following, infrared and noise signature, emissions with alternate fuels, and endurance. The results of these tests would then be analyzed, differences between desired and actual chracteristics would be determined, and recommendations for improvements would be defined.

Major Tasks:

The major task activities recommended for Phase I are as follows:

1.0 Obtain generator set
2.0 Modify generator set package
3.0 Install engine
4.0 Preliminary response testing
5.0 Engine testing under load (500 hours)
    Gasoline - 200 hours
    Diesel - 150 hours
    Kerosene - 150 hours
6.0 Infrared radiation demonstration
7.0 Noise measurement
8.0 Load following capability checks
9.0 Design load unit
10.0 Fabricate load unit

Estimated Program Costs ($ thousands):

Phase I

Direct labor costs	$ 38
Overhead costs (@ 125%)	$ 48
Material costs	$ 90
Other direct costs	$ 9
General & Administrative (@ 25%)	46
PHASE I TOTAL	**$230**

2) Phase II. Field Testing with USAF Duty Cycle Requirements.

Objective:

To demonstrate engine/generator system performance and endurance in the field under actual USAF duty cycle requirements.

Approach:

This phase would follow the completion of the generator matching program and would be an extension of the laboratory performance and endurance tests. A two task program is recommended. In Task 1 of this program, a Stirling engine/generator set would be subjected to USAF duty cycle operation in the field. The performance and functionality would be evaluated and improved to meet specifications. The unit would be self-contained with all auxiliaries and controls but it would not be configured in a military package. The emphasis of Task 1 testing would be on problem definition as a result of actual field/duty cycle utilization. Resultant problems would then be resolved through design and/or hardware changes prior to entering into Task 2.

Task 2 of Phase II would consist of endurance field tests with a simulated USAF duty cycle. Three identical, self-contained Stirling engine/generator sets would be fabricated. The results of a 2000 hour endurance test would be utilized to establish the mean time between failure (MTBF).

Major Tasks:

Task 1

1.1 Specify test program
1.2 Prepare engine generator sets
1.3 Installation and set-up in field
1.4 Monitor field tests for six months
1.5 Review and analyze test data
1.6 Design, hardware finalization, and upgrade systems

Task 2

2.1 Specify test program
2.2 Assembly and acceptance of three test engines
2.3 Fabricate three engine generator sets
2.4 Installation and set-up in field
2.5 Monitor field tests for 12 months
2.6 Review and analyze test data

Estimated Program Costs (Phase II) ($ thousands):

Task 1

Direct labor costs	$ 40
Overhead costs (@ 125%)	$ 50
Material costs	$ 85
Other direct costs	$ 4
General & Administrative (@ 25%)	$ 45
TASK 1 TOTAL	**$ 220**

Task 2

Direct labor costs	$ 105
Overhead costs (@ 125)	$ 131
Material costs	$1,100
Other direct costs	$ 11
General & Administrative (@ 25%)	$ 337
TASK 2 TOTAL	**$1,700**
TOTAL (PHASE II)	**$1,900**
GRAND TOTAL (PHASE I & II)	**$2,100**

J. Regenerative Open Cycle Gas Turbine: 750 kW System Development

Estimated Cost	Estimated Level of Effort	Estimated Length of the Development Work
$10,000,000	64 person years	60 months

Objective:

To develop the capability to produce a 750 kW open cycle regenerative gas turbine with high efficiency, long life, long MTBF, low emissions, and a low acquisition cost. This implies six sub-objectives:

1) Develop a water-cooling system to enable high turbine inlet temperatures to be used.

2) Develop ceramic components so that component life is increased under high cycle temperatures.

3) Develop preventative diagnostics, monitoring, system shutdown, and retirement for cause programs to reduce O&M costs, to prevent unecessary failures, and to prolong safe and reliable service.

4) Develop combustion chamber designs to control emissions.

5) Develop computer aided design and manufacturing (CAD/CAM) technologies to lower the high acquisition costs.

Specifications:

- Turbine inlet temperature to be 1400 - 1700 degrees Celsius.
- Cycle efficiency of 40 - 50 per cent.
- Pressure ratio of 25 - 30: 1.

• Mean time between overhauls of 10,000 hours.

Approach:

The program will be developed in three phases. The Phase I effort will be a systems analysis and feasibility study. Such a study will enable the delineation of the research work that should be specifically targeted towards the identified (750 kW) terrestrial units. This phase will also set the technical goals for the next phase.

Phase II will address the development of individual components and subsystems. Detailed analysis, design, fabrication and testing will be carried out. Based on the results, design and manufacturing procedures will be specified.

Phase III will comprise the integral design of an open cycle regenerative gas turbine system that incorporates all the improvements tested and proven under the prior phase. This phase will involve the synthesis, design, fabrication and testing. Finally, design, production and operating procedures will be documented.

Major Tasks:

PHASE I: RESEARCH REQUIREMENTS ANALYSIS

1.0 Review the significant research programs for possible technology transfer or induction.

2.0 Analyze the research requirements to achieve the major objectives.

3.0 Conduct a detailed cycle study of the advanced systems that meet the objectives.

4.0 Select candidate systems and prescribe specifications for the following phase.

5.0 Develop a water-cooling system.

5.1 Evaluate candidate water-cooling configurations.

5.2 Design and test promising water-cooling configurations in hot rotating cascades.

5.3 Design a gas turbine with a successful water-cooling configuration.

5.4 Test and evaluate the system.

5.5 Produce a design guide and document the study.

6.0 Develop Ceramic Components

6.1 Analyze, design, fabricate, test and evaluate ceramic turbine blades.

6.2 Analyze, design, fabricate, test and evaluate ceramic turbine disks.

6.3 Analyze, design, fabricate, test and evaluate metal matrix composite shafts.

6.4 Analyze, design, fabricate, test and evaluate ceramic combustors.

6.5 Analyze, design, fabricate, test and evaluate ceramic regenerators.

6.6 Develop integrative or synthesized performance with all the tested ceramic components.

6.7 Fabricate, test and evaluate an integral system.

7.0 Develop Preventive Diagnostics Monitoring System

7.1 Conduct causes for failure analysis.

7.2 Design diagnostic tools.

7.3 Fabricate, test and evaluate a preventive diagnostics monitoring system.

8.0 Develop Low Emission Combustor Systems

8.1 Study emission mechanisms under intense combustion environments.

8.2 Evaluate candidate low emission combustors and select systems for testing.

8.3 Design, fabricate and test selected combustor configurations.

8.4 Develop design and production documents.

9.0 Develop CAD/CAM Technologies

9.1 Conduct a value analysis of components.

9.2 Conduct a product and process design and analysis.

9.3 Develop detailed CAD/CAM analyses of high value components.

9.4 Select appropriate processes to minimize total process costs.

9.5 Develop CAD/CAM process guidance document for the specific gas turbine cycle.

10.0 Develop Computer Controlled Continuous Diagnostics

10.1 Analyze the critical thermal, mechanical and electrical parameters for monitoring purposes.

10.2 Survey the computer controlled instrumentation.

10.3 Identify and design sensors integral with the components.

10.4 Design, test and evaluate a specific system.

10.5 Develop a design guide.

PHASE II: INTEGRAL SYSTEM DESIGN AND TESTING

11.0 Design a gas turbine system incorporating the proven/promising developments from Phase II.

12.0 Fabricate, test and evaluate the systems.

13.0 Develop a guide for design, production and operation of an advanced system.

The program duration will be sixty (60) months as indicated in the attached program schedule.

The program cost is expected to be $10 million as detailed in the attached table.

Estimated Program Costs:

Note: The following estimates have been made on a task basis. Total program estimates are provided on a structural basis:

	Task	Program Cost (K$)
1.0	Review/Tech. Transfer	100
2.0	Research Requirements Analysis	100
3.0	Advanced Cycle Study	100
4.0	Candidate System Selection	100
5.0	Develop Water-Cooling System	600
6.0	Develop Ceramic Components	1,500
7.0	Develop Preventive Diagnostics System	500
8.0	Develop Low Emissions Combustor System	1,000

9.0	Develop CAD/CAM Technologies	900
10.0	Develop Computer Controlled Diagnostics	800
11.0	Design Advanced Gas Turbine	800
12.0	Fabricate, Test, Evaluate System	3,200
13.0	Develop Design and Production Guide	300
	TOTAL:	$10,000

Direct labor costs	$ 2,000
Overhead costs (@ 125)	$ 2,500
Material costs	$ 3,500
General & Administrative (@ 25%)	$ 2,000
TOTAL	**$10,000**

VIII. Facilities Electric Generating System (FEGS) Analysis

A. Approach

The basic strategy for this additional task was to capitalize upon work accomplished during the performance of the previous tasks. The research team and the project engineer agreed that the limited resources available should be allocated to understanding the operational requirements for FEGS and to the analytical task, as opposed to further technology studies. Therefore, the modified ATES, as developed for the MEP portions of the analysis, also served as the technologies data base for this task.

Because the ATES also includes information regarding certain renewable energy systems which were not appropriate for MEP applications, the project manager decided to incorporate those systems into the analysis. Thus, flat plate photovoltaic, photoelectrochemical and actively cooled photovoltaic power plants as well as horizontal axis and vertical axis wind turbines were compared with the requirements information on FEGS, generated as part of this task. Unlike the other ten technologies, however, no attempt was made to validate or update the ATES data on these renewable energy technologies.

Because the ATES included information regarding 5,000 kW power plants, the project manager also decided to incorporate a consideration of these large systems into the FEGS analysis. Once again, funds were not available to validate or update ATES data, although validated data was available for the ten technologies previously considered. All values used in the analysis are incorporated into Appendix A.

The first step in the FEGS analysis was to determine the requirements imposed by facilities support missions. The approach developed in Task 1, (Mobile Power System Analysis), was utilized here, although the survey sheets were modified slightly to reflect the differences between MEP and FEGS applications. A thirteenth parameter was added, as appropriate to facilities' applications, namely that of "Thermal energy available." This variable incorporates a measure of the operational value of cogenerated heat, which could be used for space heating, water heating, etc. in facilities' applications. The statement of work for this task required the research team to report on issues and concerns which were raised during the requirements definition process, which are included in the Integrated Logistics Support Program under Air Force Regulation 800-8.

The second step of the analysis was to compile the data on FEGS requirements into appropriate sets for analysis. Once these applications scenarios were established, MADM was used to evaluate the operational effectiveness potential for appropriate technologies in each application. A corresponding cost analysis was performed, using the methodology presented in Section V.A., p. 28 above.

Unlike MEP applications, there are significant and defineable differences in operational duty cycle for different facilities electric applications. The principal, current FEGS applications are for emergency/backup power plants which provide power to critical USAF consumers in the event of a power disruption. These plants are typicallly exercised once a week or once a month, and are functionally operational on an unpredictable schedule.

Because cost projections are heavily dependent on duty cycle, the choice of a reasonable variable was important here. In peacetime, FEGS backup plants are typically run 50 - 80 hours per year, equal to a one per cent duty cycle. In the event of national emergency however, these plants might be run at 100 per cent duty cycle for the duration of the emergency.

The typical trade-off in power plant selection is between first cost vs. fuel cost. Power plants which are highly fuel efficient can be expected to be more expensive to build. By emphasizing peacetime duty cycle requirements, USAF could end up with grossly inefficient power plants in an emergency situation. By emphasizing emergency requirements, USAF could spend an order of magnitude more in procurement costs for systems which are never used.

The research team arbitrarily designated a one-eighth duty cycle for evaluating the potential cost effectiveness of these plants, in order to realize a reasonable, compromise figure. This approach assigns a small premium to fuel efficiency, and serves to eliminate grossly inefficient systems. At the same time, it recognizes the principal function of these power plants, which is to provide a backup generating capability.

The second current FEGS application is that of remote site power generation. USAF operates over one hundred such plants at locations worldwide. For these applications, the research team assumed a 100 per cent duty cycle.

Two new FEGS applications may come into existence as a result of considerations now underway. Since 1982, DoD and USAF have been paying an increased level of attention to the issue of base self-sufficiency. This concept could represent a departure from current practices in which the local utility is considered the prime power source for most Air Force Bases. One option for providing base self sufficiency is that of power generation within the fence, i.e. within the base perimeter. We have assumed a 100 per cent duty cycle for this scenario which tests the operational effectiveness and economics of this approach to base self sufficiency.

Finally, Air Training Command and, more recently, Strategic Air Command have initiated the construction of centralized aircraft support systems (CASS). CASS would replace the flightline MEP systems as the principal method for providing power for aircraft support. Current designs rely on utility power converted to 400 Hertz precise power through the use of motor driven generators. Backup capability would be provided by the MEP systems retained in stock. An alternative to this approach would be the use of autonomous CASS power plants by the Base Civil Engineers. In testing this potential application, the research team estimated a one-third duty cycle as representative of the application.

Like duty cycle, fuel selection is an important variable for facilities' energy systems. Because natural gas is an inexpensive fuel which is available at most Air Force bases, the use of this fuel is a viable alternative for back-up, CASS, and base self-sufficiency systems. The research team, guided by the availability of data and the assumptions included in the ATES, considered natural gas fuels for systems larger than 100 kW for self-sufficiency, CASS, and back-up applications. Residual fuels were also considered where designated by the ATES.

It should be noted that available data does not reflect all of the potential for natural gas combination. Moreover, cost results are highly dependent on fuel price assumptions. For these reasons, caution should be used in interpreting the results of cost comparison among systems using different fuels.

The final step of this task was the interpretation of analytical results.

B. Results

1. Field Interviews

During July and August of 1983, Applied Concepts' research team conducted field interviews and held discussions with FEGS maintenance personnel, base civil engineer officials, and BCE management and planning officials in the following locations:

Headquarters, Strategic Air Command, Offutt Air Force Base, Nebraska

Headquarters, Air Force Engineering and Services Center, Tyndall Air Force Base, Florida

Headquarters, Peterson Air Force Base, Colorado

Headquarters, Lowry Air Force Base, Colorado

Headquarters, Langley Air Force Base, Virginia

Headquarters, Dover Air Force Base, Dover, Delaware

Headquarters, Andrews Air Force Base, Maryland

Headquarters, United States Air Force, The Pentagon, and Bolling Air Force Base, D.C.

Base civil engineer (BCE) and headquarters staff personnel provided the responses used in formulating the User's Preference Package for MADM. Time and contractual constraints did not permit the solicitation of opinion Air Force wide through a mail survey. The number of respondents in each category were as follows:

1)	Emergency/Backup Applications:	19
2)	Base Self Sufficiency Applications:	19
3)	Remote Facility Applications:	8
4)	CASS Applications:	3
	TOTAL RESPONSES:	49

Figure VIII-1 presents a summary of results for parametric evaluation. It can be observed that FEGS users rated reliability as the most valuable characteristic, as opposed to quality of power output, which was of greatest concern for MEP users. This is probably due to the fact that 400 Hz precise power is commonly generated by MEP systems or by motor generator sets. The common FEGS power is 60 kW utility purchased electricity. Fuel consumption rate was of higher concern to the BCE respondents, while mobility factors, size and weight were of lower concern, as would be expected. The differential between parameter values was greater for FEGS applications. This probably represents the greater flexibility demanded of MEP systems, which must operate in multiple environments and in multiple applications.

Figure VII-2 presents summary data on permanently installed generators in CONUS, listed as real property as of September 1982. In addition, Air Force bases normally have an inventory of portable generators of varying capacity, which are assigned against a particular function in the event of a commercial power failure, but which can be used elsewhere on base as required. (These are referred to as EAID generators, for Equipment Authorization Inventory Data). An inventory of this equipment was not obtained by the research team. Normally, a base has between six and twelve such generators.

The great majority of the generators are in emergency/backup applications. Nearly all of them are locally procured diesel engine driven systems, although some gasoline engine driven systems exist in small sizes, and a very few turbine engines exist in large power plants. Many of the systems are older sets, some dating to the 1930s.

In addition to the CONUS generators identified above, a recent survey showed 139 USAF remote site facilities, mostly OCONUS, each with multiple backup systems, and most with a prime power plant. The end-uses for backup and remote power plants are similar. The chief difference is availability of commercial power. Typical end-uses cover the spectrum of USAF activities, including NAVAIDS, communications system support, flight operations support, computer system support, missile system support, command and control system support, etc.

2. ILS Considerations

During the interview process, the research team elicited comments from the BCE and Headquarters staffs regarding issues related to the integrated logistics support (ILS) program. Resources were not available to conduct systematic research and analysis in this area, but the project engineer and the research staff thought it valuable to assemble preliminary information in this area to be a basis for later research design. The following comments were abstracted from interview notes and completed surveys. They do not represent a balanced analysis of the ILS situation. Rather, they represent comments in response to a solicitation to identify problem areas. The comments are organized by ILS program element.

PARAMETER	SCENARIO Sufficiency	Emergency	Remote	CASS
Reliability	100	99	100	100
O&M	93	86	89	88
Start Up Time	72	77	56	37
Quality of Output	72	53	39	58
Fuel Consumption	64	55	47	77
Useful Life	61	62	65	58
Portability	51	38	25	47
Fuel Capability	50	40	36	55
Environ. Const.	37	29	28	20
Location Const.	36	31	47	37
Size	27	28	29	30
Weight	25	26	27	23
Thermal Energy	22	23	22	17

Figure VIII-1. FEGS SURVEY RESULTS

MAJCOM		1-25	26-75	76-175	176-500	501-2000	>2001
		UNIT SIZE (kW)					
SAC	Units	119	570	70	32	18	4
	MW	1	41	10	9	12	34
MAC	Units	71	104	66	60	11	3
	MW	1	5	9	23	12	13
TAC	Units	174	206	101	75	14	11
	MW	2	10	12	22	14	39
AAC	Units	39	41	27	23	35	8
	MW	1	2	3	7	34	69
ATC	Units	111	131	49	23	7	1
	MW	1	7	6	6	6	4
AFLC	Units	64	62	37	31	13	4
	MW	1	2	5	9	13	8
AFSC	Units	82	69	47	23	9	4
	MW	1	3	6	6	10	19
Other	Units	91	153	64	20	5	3
	MW	1	7	8	6	6	10
CONUS TOTAL:							
	Units	751	1,336	461	287	112	38
	(%)	25	45	15	10	4	1
	MW	9	77	59	88	107	196
	(%)	2	14	11	16	20	37

Figure VIII-2: FEGS INVENTORIES (CONUS Only)

1) Reliability and Maintainability Interface.

a. Reliability of FEGS power units is critical to insure that vital radar and telemetry data are not lost, due to power equipment failure, and that operations are not aborted.

b. The lack of standardization of FEGS power units affects the mission effectiveness capabilities of power production maintenance organizations. The multiplicity and variety of power units makes actual equipment maintenance very difficult.

c. Inadequate power or equipment system reliability, caused by unreliable equipment, poor logistics support, design inadequacies (i.e. poor fault and transient surge protection), inadequate training, and cumbersome government procurement procedures, all impacts on mission effectiveness. Costly redundancy must be designed and built into power systems supporting missile launch facilities. Emergency alternate power supplies with highly reliable and costly batteries are frequently activated. In order to insure that start-up time is not excessive during an emergency, inspection and test operations of standby generators are planned and conducted too frequently.

d. Many of the FEGS diesel generators are very old and are not run regularly. This factor has the potential to affect reliability, especially during extended operation when commercial power outages occur.

e. The reliability of FEGS generators is affected by their unnecessary complexity. The generator's reliability usually is inversely proportional to its complexity.

f. The performance characteristics of both fixed and mobile generators are becoming unacceptable in terms of the power requirements of the high technology loads which they must support. In fixed units, obsolescence of the engine generator and its ancillary equipment (turbos, fuel injectors, starters and controls) prior to the end of the facility's life is causing significant logistic problems on centrally procured and commerical units.

g. The growth of emergency generator loads/loading increases pressure for system redundancy in commercial prime power feeders to facilities in order to assure reliability and to give reverse power feeds to facilities during maintenance and repair actions.

h. Power stability is critical for uninterrupted power supply and system operation. The stability is especially critical for radar operations which take hours to reset correctly if power is interrupted.

i. EAID generators do not conform to all voltage requirements; the units are dual rated but the higher rating is 416V/240V instead of 480V/277V. Therefore, either the generators must be modified for 480V and de-rated in kilowatt output by 28% or the systems must be operated at 416V causing inefficiency and motor burnout. The maximum EAID generator rating is 150 kW; therefore, the use of EAID generators to back-up fixed generators is severely limited.

j. Maintainability and reliability testing should be planned and conducted frequently by full operational power support tests when commercial power supplies are intentionally terminated.

2) Maintenance Planning

a. Scheduled maintenance planning for FEGS generators is inefficient, since the generators are not run very often. Lack of sufficient scheduled operation can affect the reliability of the unit to start and assume the power load after having been non-operational for most of the month. The lack of regular operation of FEGS emergency backup generators limits the amount of planned maintenance training on the actual equipment.

b. The lack of acceptable operating and maintenance procedures for FEGS generators is a critical deficiency. Improper operation and maintenance results in reduced reliability, increased start-up time, and wasted fuel.

c. A standard system for fire detection and suppression should be developed and promulgated.

d. Inadequate preventative maintenance procedures for FEGS generators increases the amount of depot level maintenance needed and decreases the mission effectiveness.

e. Generator characteristics (voltage and frequency regulation, etc.) which do not meet the requirements of new "high tech" loads necessitate premature generator replacement. New generators, especially those procured for primary support to communications equipment, must be significantly oversized in order to meet enhanced load requirements.

f. Base civil engineer (BCE) units and the resident and tenant communications squadrons [i.e. the units supported] should have, and should peiodically review, a memorandum of understanding or a letter of agreement which insures that the BCE provides prompt response and support during power outages or emergencies.

g. The evolution of the concept of a centralized aircraft support system (CASS) presently includes the use of commercial power as the primary power source with aircraft ground equipment (AGE) available for use as a backup power if needed. Operational organizations plan to retain 60-65% of the authorized AGE, due to mobility mission requirements, after the CASS concept evolved as power grid systems at air bases. CASSes, as presently configured will tend to reduce the maintenance expertise of AGE personnel assigned to CASS bases. The development of a mobile CASS may be a viable option in order to improve the overall CASS program.

h. Base energy self-sufficiency is [currently] predicated on the assumption that commercial power sources always will be available as the primary source of energy for all aspects of base and flightline operations.

i. MAJCOM staffs should evaluate their future scenarios for achieving base energy self-sufficiency using centralized base power plants, large diesel generator set "clusters" at key locations, and possibly large fuel cell power production facilities.

j. Emergency backup generators are tested and run once a month or once every two months; the generators average about 50 hours of actual test or backup operation annually. An increased emphasis in using the backup generators more frequently would lead to more frequent hands on maintenance experience by power production personnel.

3) Support Equipment

None.

4) Supply Support

a. Spare parts for many of the old FEGS generators are not available through Air Force supply channels because the generators no longer are being manufactured.

b. There is a long lead time to receive spare parts for the old FEGS generators, if they are available at all.

c. The normal repair stock of spare parts is not available from manufacturers after 10 years from purchase date. Since FEGS generator spare parts normally are not available through regular Air Force supply channels, long delays are commonly experienced in obtaining or having parts made for the older diesel generator. A six month spare parts lag is not unusual for the older systems.

d. The availability of spare parts for the older FEGS units causes maintenance problems and creates encroachments on the "uptime" ratios required by the loads supported by these generators.

e. The lead time to obtain a replacement generator is excessively long, up to two years after requisition. "Reserve" spare parts inventories must be maintained longer than normal because of the possibility of equipment failure until replacement generators are received.

f. Detailed part number and component breakdown information for the procurement of replacement parts is not readily available.

g. The quantities of reserve fuel for emergency backup generators varies greatly (e.g. from 6 hours to 15 days) among units and commands. Most air bases do not have sufficient reserve fuel supplies to support emergency bakcup generators should there be an extended power outage. This revelation was substantiated during recent USAF commercial power interruption tests.

h. The availability of spare parts for the old diesel generators in missile silos is a recurring problem. These older generators are maintenance intensive and require higher levels of power production maintenance expertise. Lack of standardization of generators is a continuing problem.

i. Spare parts for FEGS generators obtained from local dealers normally were easy to obtain and local generator equipment representatives generally provided prompt and responsive support when contacted.

5) Packaging, Handling, and Transportation

None.

6) Technical Data

Power production equipment maintenance personnel are trying to maintain old systems using inaccurate, outdated, and poor equipment manuals.

7) Facilities

a. Power support requirements for all types of equipment, especially with increased usage of computer systems, need to be carefully planned when developing base facilities.

b. Planners developing appropriate power support equipment for the Peacekeeper should consider the entry constraint caused by the four foot diameter entry portal in the existing Minuteman silos.

c. There are 20-30 thirty to sixty kilowatt generators at the scattered aircraft firing ranges in CONUS. Power production maintenance personnel frequently must be sent to the ranges to support firing exercises. The introduction of a new, or innovative, power generating technology at the ranges would reduce frequent TDY travel by power production personnel to the ranges so they could better support their assigned base power producion requirements.

8) Manpower Requirements and Personnel

There is a lack of trained, prime power production personnel in some of the MAJCOMs.

9) Training and Training Support

a. Personnel technical skill expertise and skill levels are inadquate for airmen to properly operate and maintain high voltage, power

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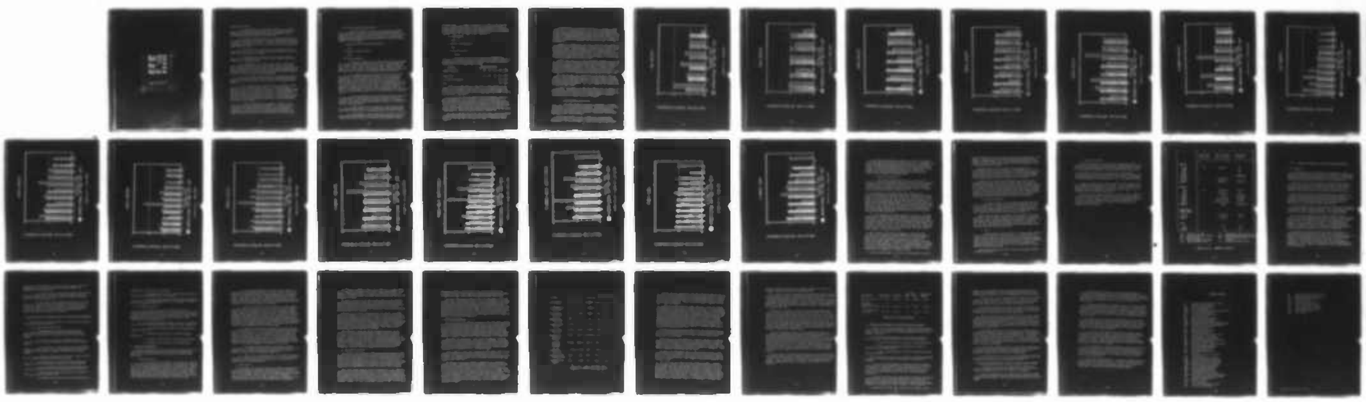

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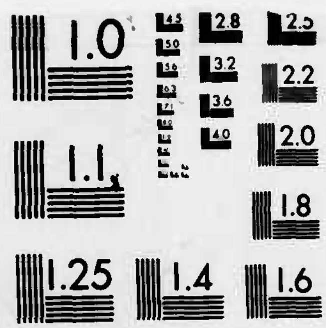

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production facilities.

b. Non-standardization among FEGS generators has a definite impact on the ability of maintenance personnel to effectively maintain a wide variety of different types, output levels, and models of FEGS generators made by numerous different manufacturers.

c. The lack of built-in redundancy in power systems does not allow regular equipment maintenance and training unless mission "down time" is granted. The insufficient amount of hands on training which is actually performed severely limits the ability to properly operate the systems and causes operator errors.

d. The technical training of power production personnel, to include OJT when necessary, is inadequate for the assortment of generators which must be operated and maintained.

e. Power production personnel are not thoroughly trained or experienced in troubleshooting techniques essential to keep a unit fully operational in a minimum of time.

f. Commanders need to be better informed about the duties of power production personnel at prime power plants. Senior officers who visit or inspect power plants have the impression that the airmen should be busily working most of the time. While, in fact, their responsibilities at the plants primarily are concerned with the continued effective operation and maintenance of the power production equipment.

g. Airmen trained as power production personnel (AFSC 542x2) at the nine week course at Sheppard AFB are not instructed thoroughly about turbines or in troubleshooting. These two areas of instructiion could be improved.

h. Most military power production personnel assigned to CONUS base civil engineer power production offices are familiar with MEP generators and have not been exposed to the wide variety of commercial FEGS generators which they are assigned to maintain. It is extremely difficult for military power production personnel to obtain a quota to attend remedial or refresher training at the technical training center at Sheppard AFB. Consequently, power production personnel are cross-training out of the AFSC into more interesting career fields which offer personal career growth and job satisfaction.

i. Military power production specialists presently are not trained to cope with or understand the complicated electric, electronic, solid state, and computer associated equipment. The environmental management contol systems (EMCS) being used on most bases require that power production specialists have an understanding of heating and air conditioning systemic requirements, which they currently do not possess.

10) Logistic Support Resource Funds

Logistic funding at one base was insufficient to purchase a backup power system for cooling an extensive data processing computer system, although a backup power system was funded for the computer system. Consequently, when commercial power is interrupted, the data procesing systems overheat and work must cease because there is no external cooling capability for the equipment.

11) Logistics Support Management Information

None.

12) Computer Resources Support

None.

13) Energy Management

a. Some remote facilities, such as satellite control or tracking sites, are not linked to commercial power sources. A direct commercial power linkage to FEGS power generation units, where feasible, would ease the need for standby reserve units and would permit the sale of excess power to the utility company. This suggested mode of operation would allow FEGS power units to run at full capacity and efficiency more often.

b. An integrated power system which uses coal as the primary fuel should be developed to generate electricity, heat, and cooling (cogeneration). The Air Force should evaluate a recent Department of Energy project which accomplishes these functions but also directly generates about 30% of the coal energy output as liquid methanol fuel. If this is practical, an Air Force base would have self-generated liquid fuel (methanol) to operate the base vehicle fleet. If possible, modular 5-10 megawatt units might be developed, as standard prime power plants for bases, on a turn-key basis. The basic coal fuel might need to be converted into a more easily handled product such as a coal oil mixture or coal water slurry.

c. Base energy management personnel should arrange for operation of FEGS generators in conjunction with power supplied by local power utilities to meet power requirements during peak periods. This suggested procedure will save base energy funds and will provide for a better use of emergency backup generators.

d. Several bases rely on a single power feeder cable as their sole commercial power source. An alternate power supply cable should be considered for power support use during emergencies or natural disasters.

e. The planning for future energy self-sufficiency at air bases should emphasize development of power generating technologies that are founded on sustained utilization of natural energy resources available to the CONUS bases. For example, planning for energy self-sufficiency at bases in Virginia could focus on using coal as a primary fuel source, during extended global conflict or extended disruption of the petroleum pipeline, while bases in other parts of CONUS could plan on using natural gas, geothermal, or solar power as most appropriate.

14) Survivability

None.

15) ILS Test and Evaluation

None.

3. Analytical results

a. General

Based upon the results of interviews with USAF BCE and Headquarters personnel, upon the real property inventory data, and upon the technologies information available in the ATES, the following scenarios were analysed using the MADM computer model:

Scenario	Power Levels (kW)					
Emergency/Back up	5	60	100	250	750	5000
Remote Site	5	60	100	250	750	5000
Base Self Sufficiency					750	5000
CASS					750	5000

In each case, MADM compared the desirable characteristics for the applications (contained in Figure VIII-1) with the characteristics for appropriate technologies at each power level (contained in Appendix A). The resulting utility values for each of three years, 1985, 1990, and 2000, are presented in Appendix G.

Cost projections were also made for the technologies and scenarios under consideration. This information is contained in Appendix E. Emergency/backup systems were assumed to have a one eighth duty cycle. Base self sufficiency and remote site applications were assumed to have a 100% duty cycle. CASS applications were assumed to have a one-third duty cycle. Appendix E does not contain the value for the two CASS cost projections, but those values may be easily calculated from the information in the appendix, using the formula presented in Section V.A.

For larger systems (>100 kW) the most cost effective fuel was assumed, as identified by the ATES, except for remote site applications, where logistical considerations were assumed to require a refined petroleum product.

A problem arose in establishing a baseline for comparison of FEGS technologies. As indicated above, FEGS systems are not standardized. Because nearly all FEGS systems are diesel engine driven (DED) systems, the research team chose to use the MEP tactical utility DED generator in each category as the baseline for all FEGS applications from 5 to 250 kW. For 750 kW, the familiar USAF Bare Base turbine was used. For 5,000 kW, the research team used the turbocharged DED system as defined in the ATES as the baseline.

Because the utility grid is the current source for prime power and for CASS systems, the research team made a comparison with this power source in these applications. Because dependency on external power sources is the matter of concern, operational effectiveness for utility power is meaningless. In the case of CASS and base self sufficiency FEGS therefore, an operational effectiveness baseline was established as for the other scenarios. The cost effectiveness baseline was taken to be utility power at an average annual cost of $0.05 per kWH.

The FEGS analytical results show some marked differences with the MEP projections. Most noteworthy is the fact that the analysis indicates no particular potential for increased operational effectiveness for any of the advanced technologies considered. A consideration of Figures VIII-3 through VIII-18 indicates that in no case except the 5 kW emergency / backup and remote applications does the projected effectiveness of advanced technologies in the year 2000 exceed the DED baseline by as much as 20%.

The principal reason for the relative attractiveness of baseline systems is that reliability, operability and maintainability, and useful lifetime rate very high among FEGS users, while size, weight, portability, and environmental constraints rank low. The former characteristics favor well known, tested technologies. The latter parameters are characteristic of new technology systems.

The major discriminator for FEGS applications, then, is relative cost effectiveness. According to the cost statistics used in this analysis, which were chosen not to favor new technology systems, the potential exists for substantial cost savings over the baseline systems, if advanced technology electrical energy plants are introduced.

b. Emergency/Backup Applications

All of the advanced technologies considered for all power ranges from 5 to 5,000 kW indicated only minor improvements in operational effectiveness over the baseline technologies. Within the level of precision for this analysis, all of the alternatives considered rank equally well with current systems in terms of operational effectiveness. (See Figures VIII-3 through VIII-8).

In the middle ranges, i.e. 60 - 250 kW, none of the advanced technologies indicate any potential for enhanced cost effectiveness. Opportunity exists for improvement in smaller and larger sizes, however.

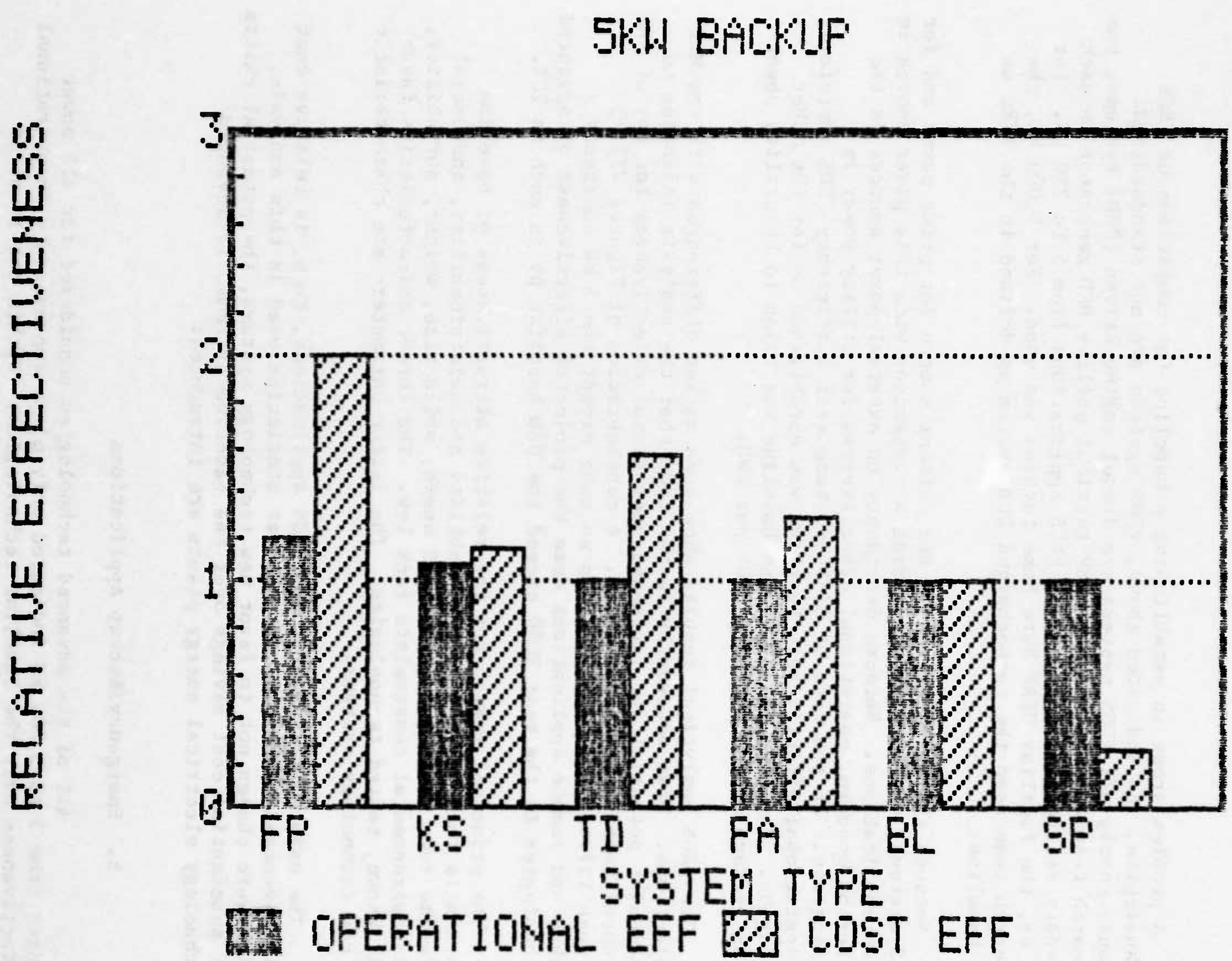

FIGURE VIII-3: 5KW BACKUP

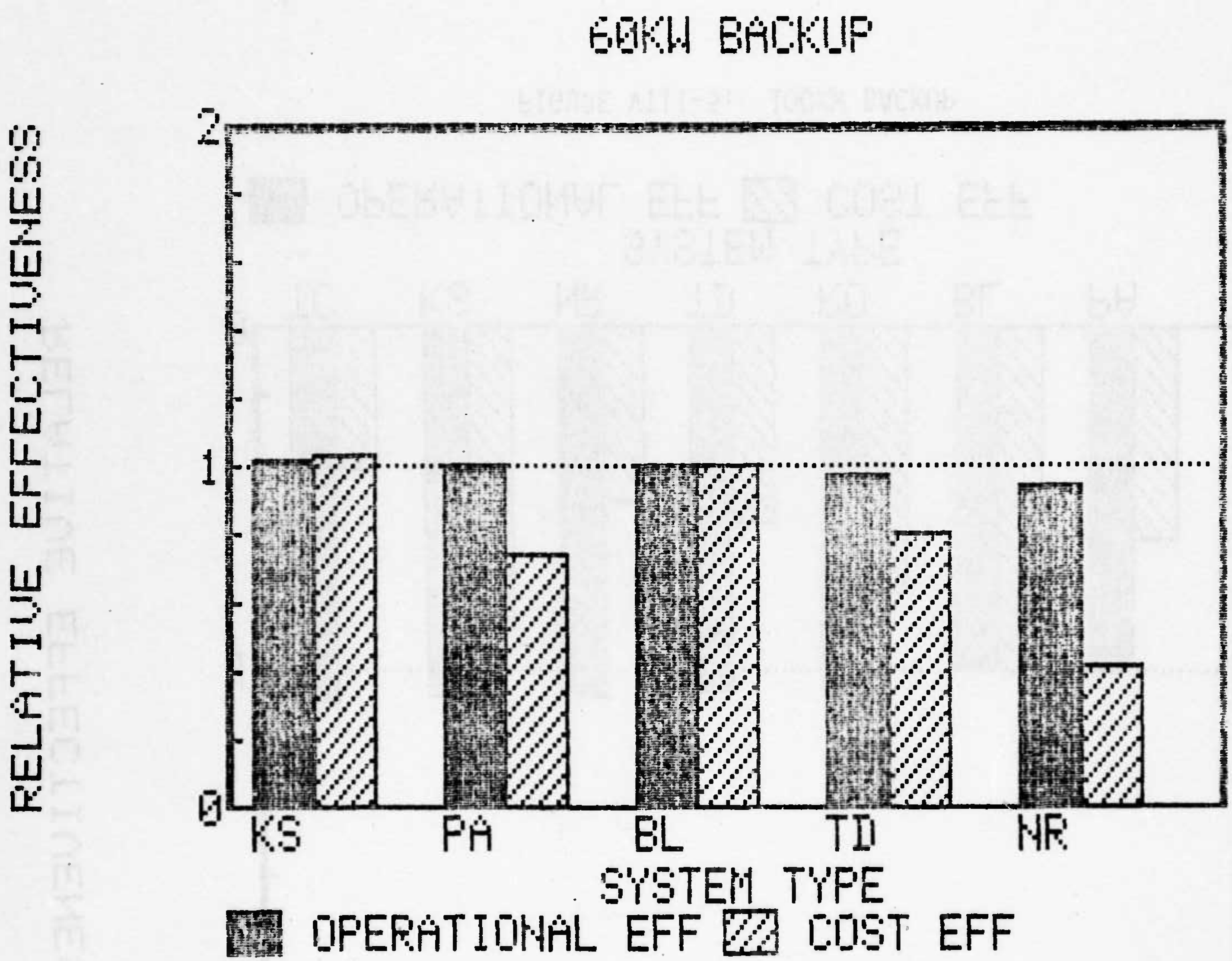

FIGURE VIII-4: 60KW BACKUP

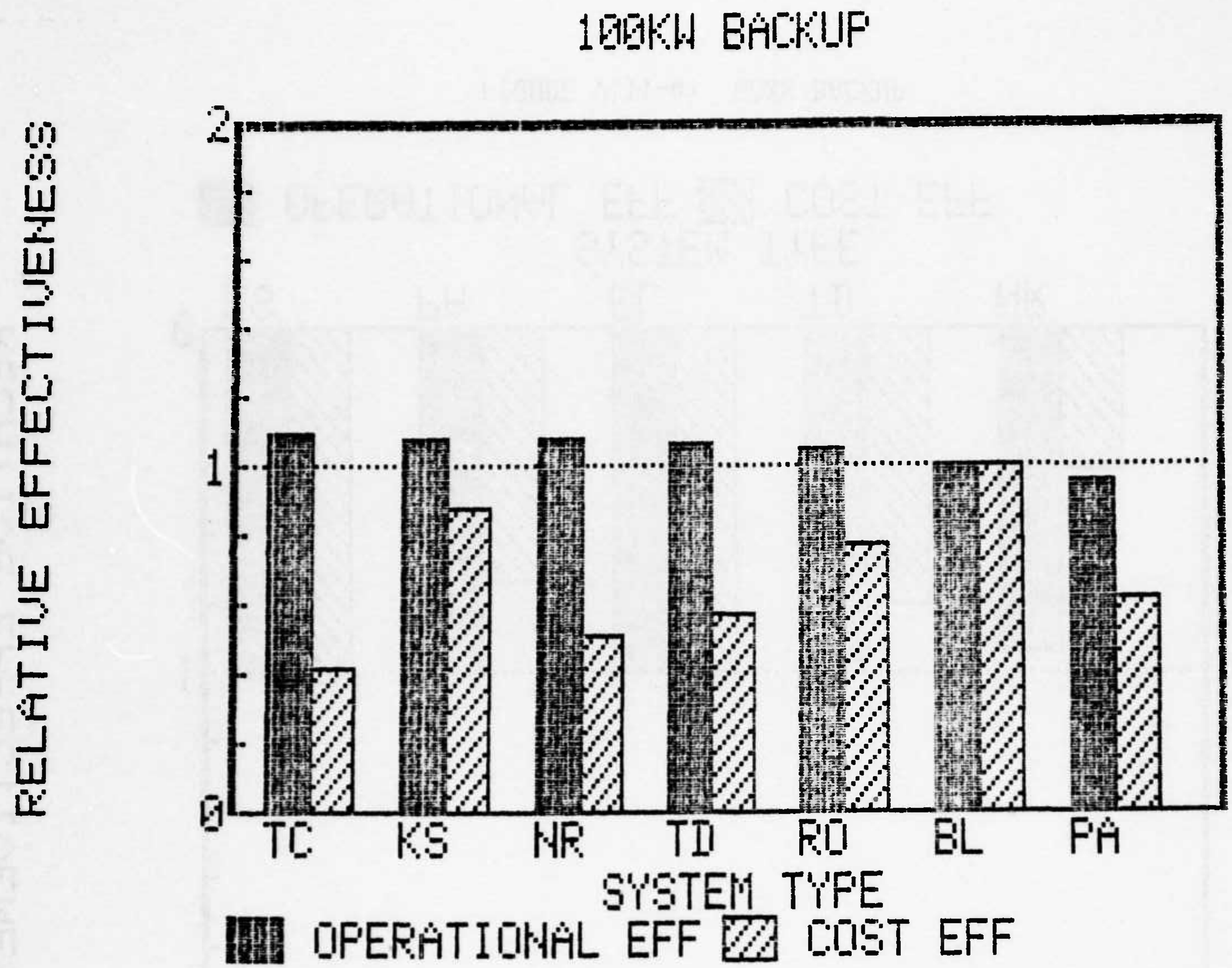

FIGURE VIII-5: 100KW BACKUP

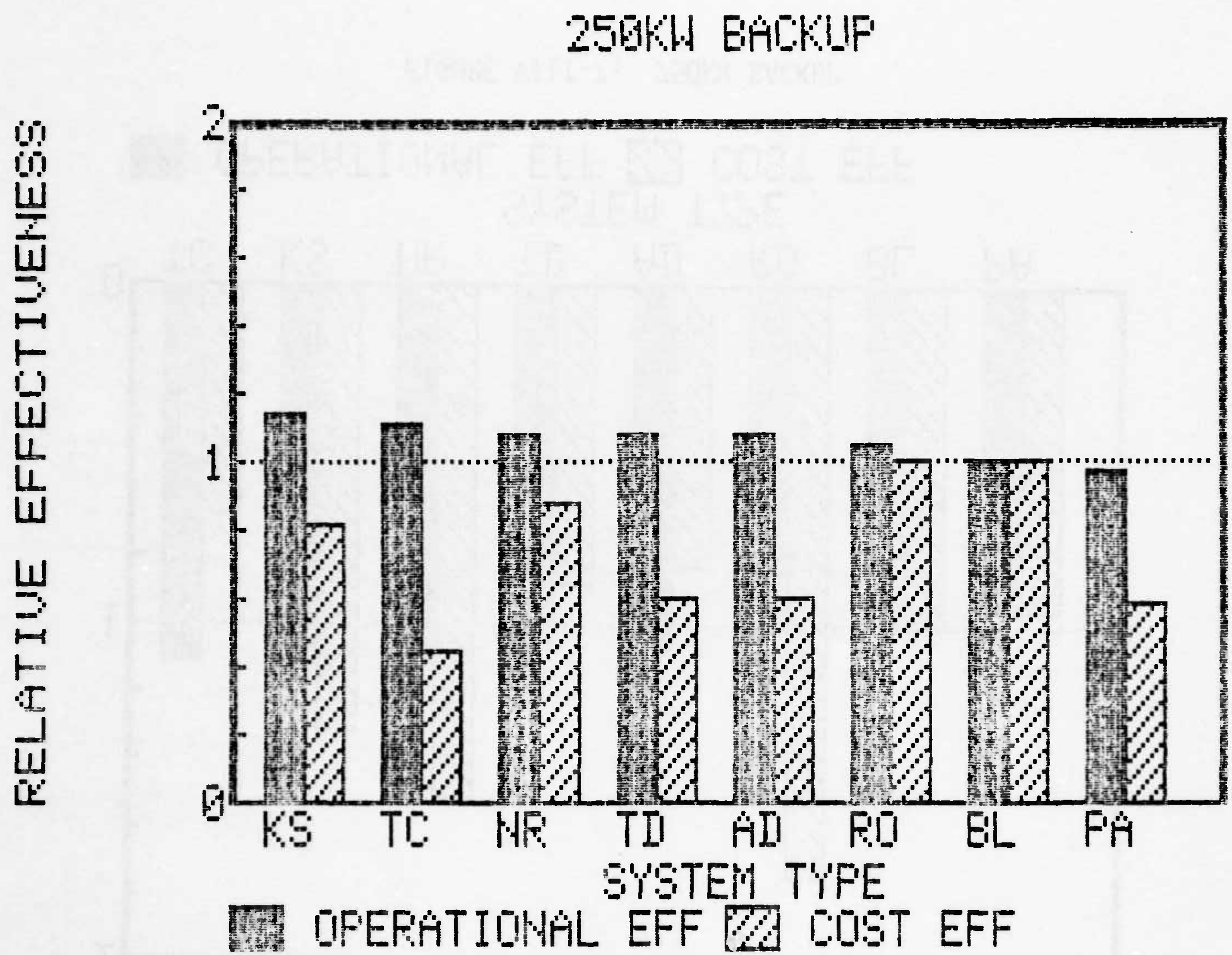

FIGURE VIII-6: 250KW BACKUP

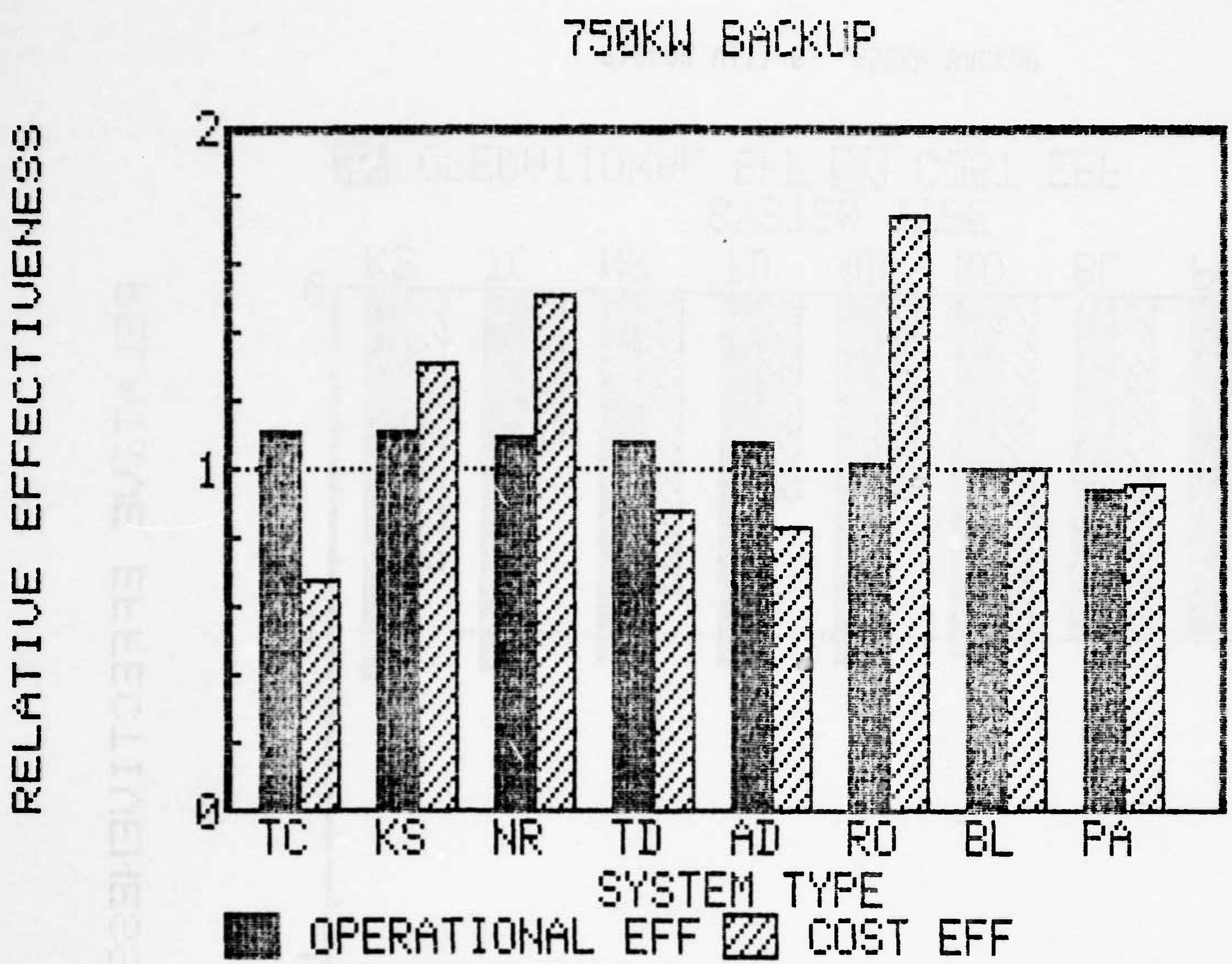

FIGURE VIII-7: 750KW BACKUP

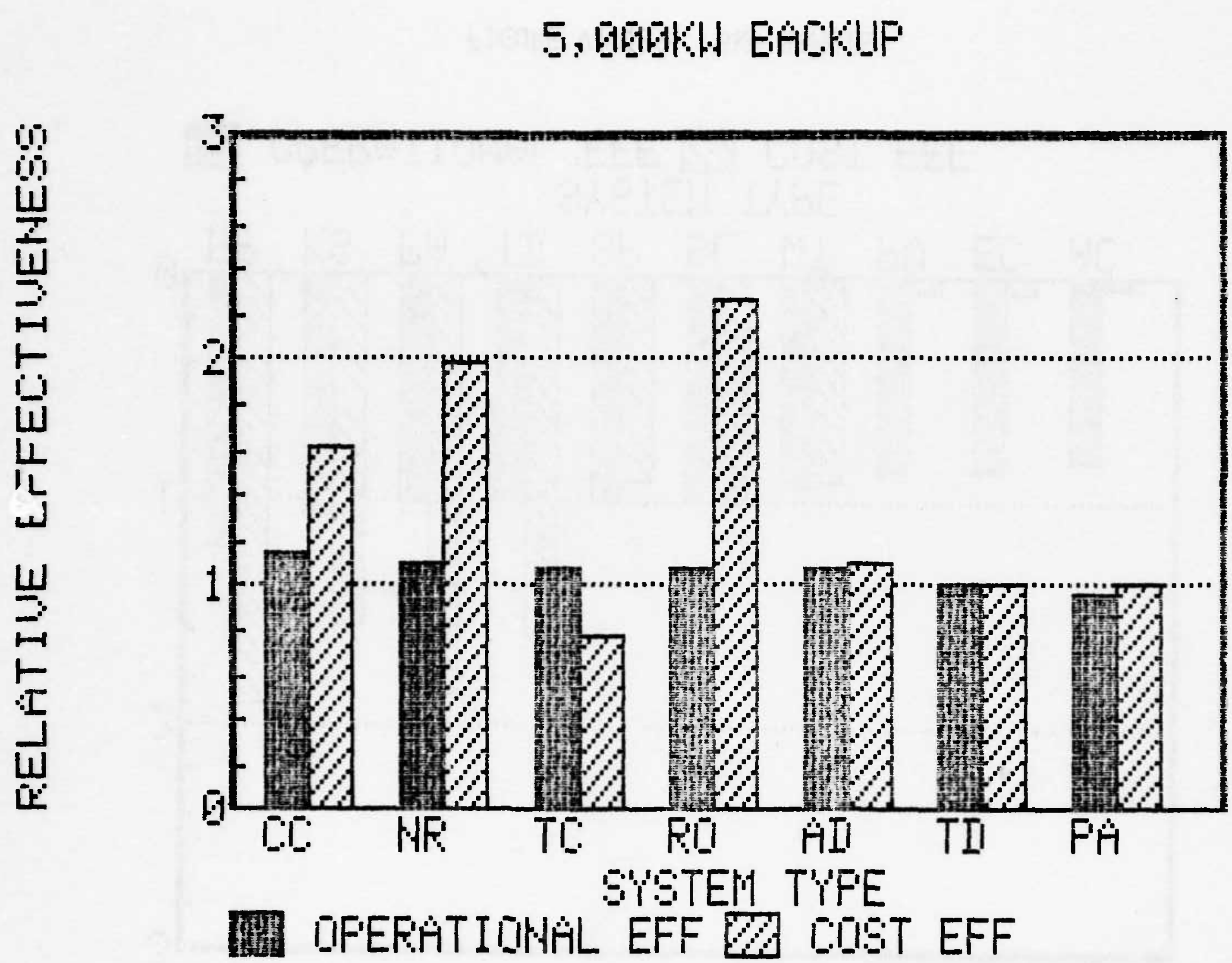

FIGURE VIII-8: 5,000KW BACKUP

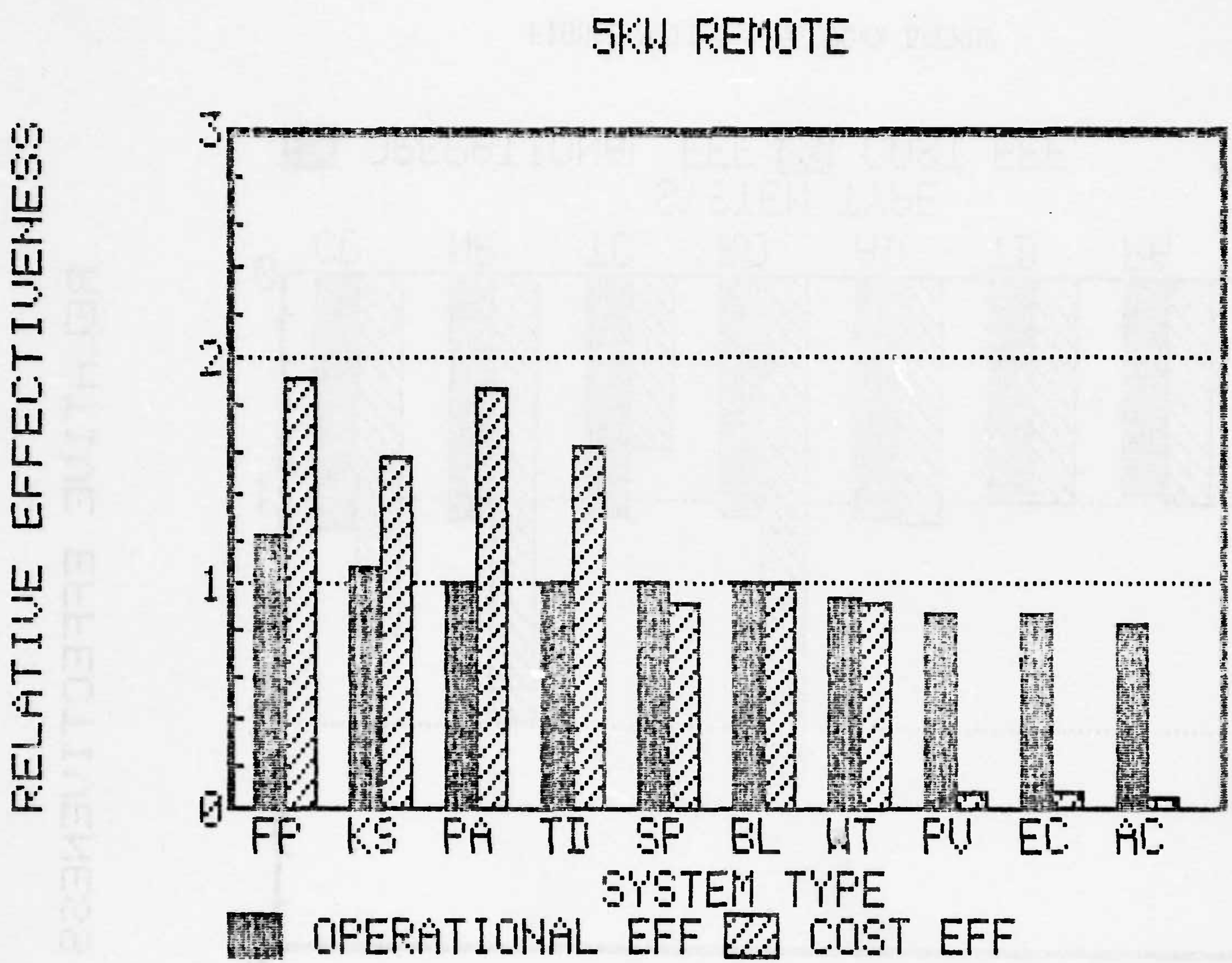

FIGURE VIII-9: 5KW REMOTE

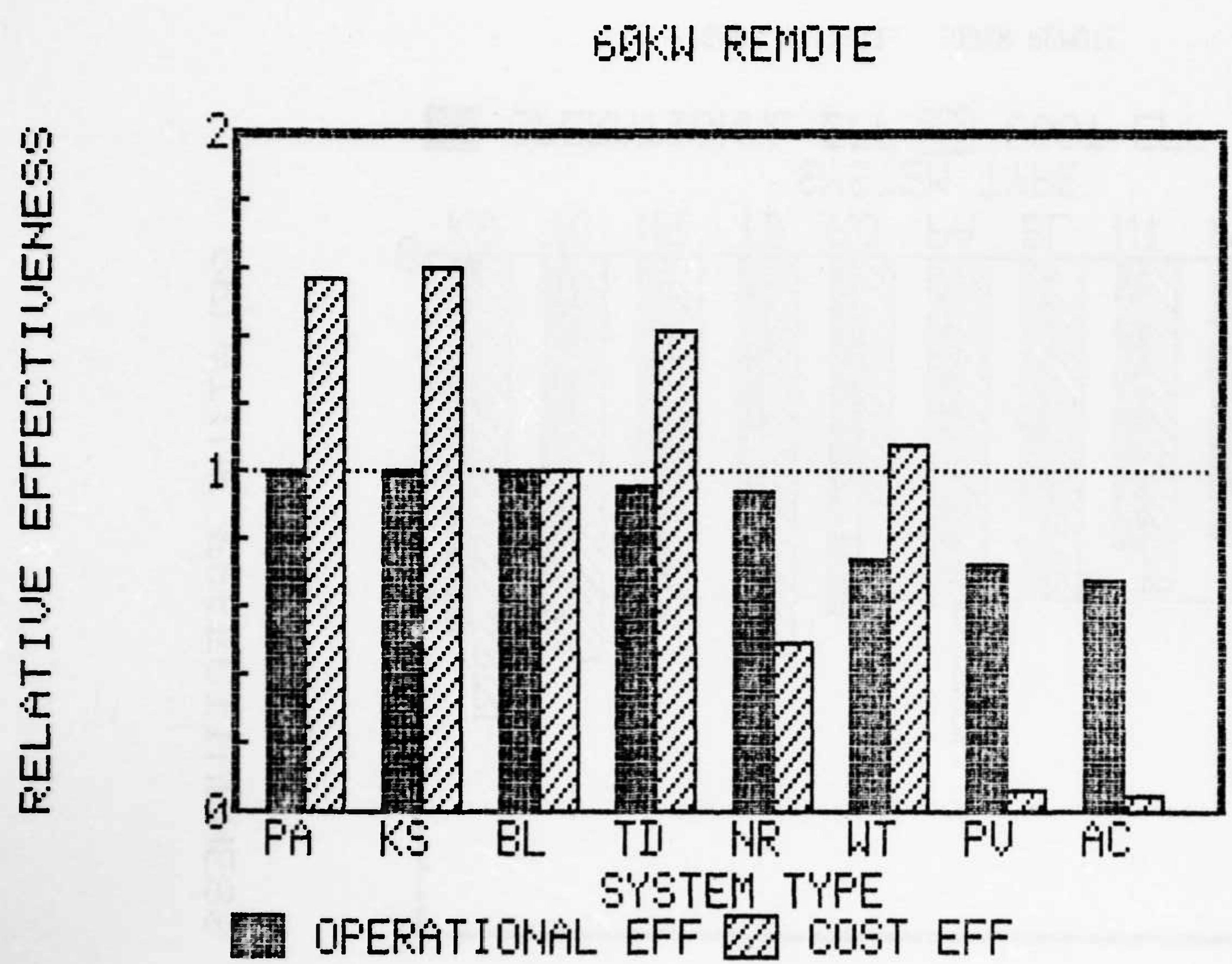

FIGURE VIII-10: 60KW REMOTE

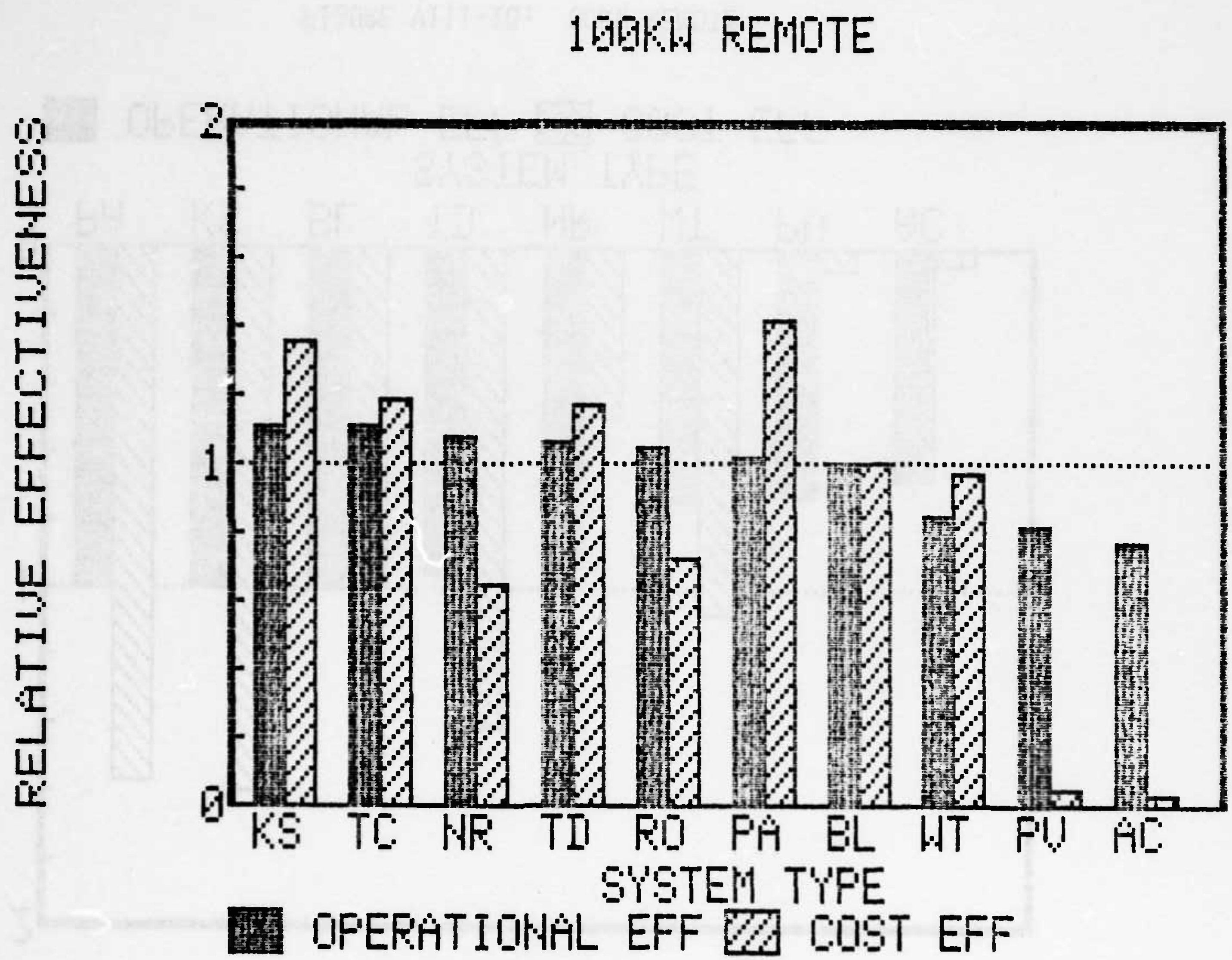

FIGURE VIII-11: 100KW REMOTE

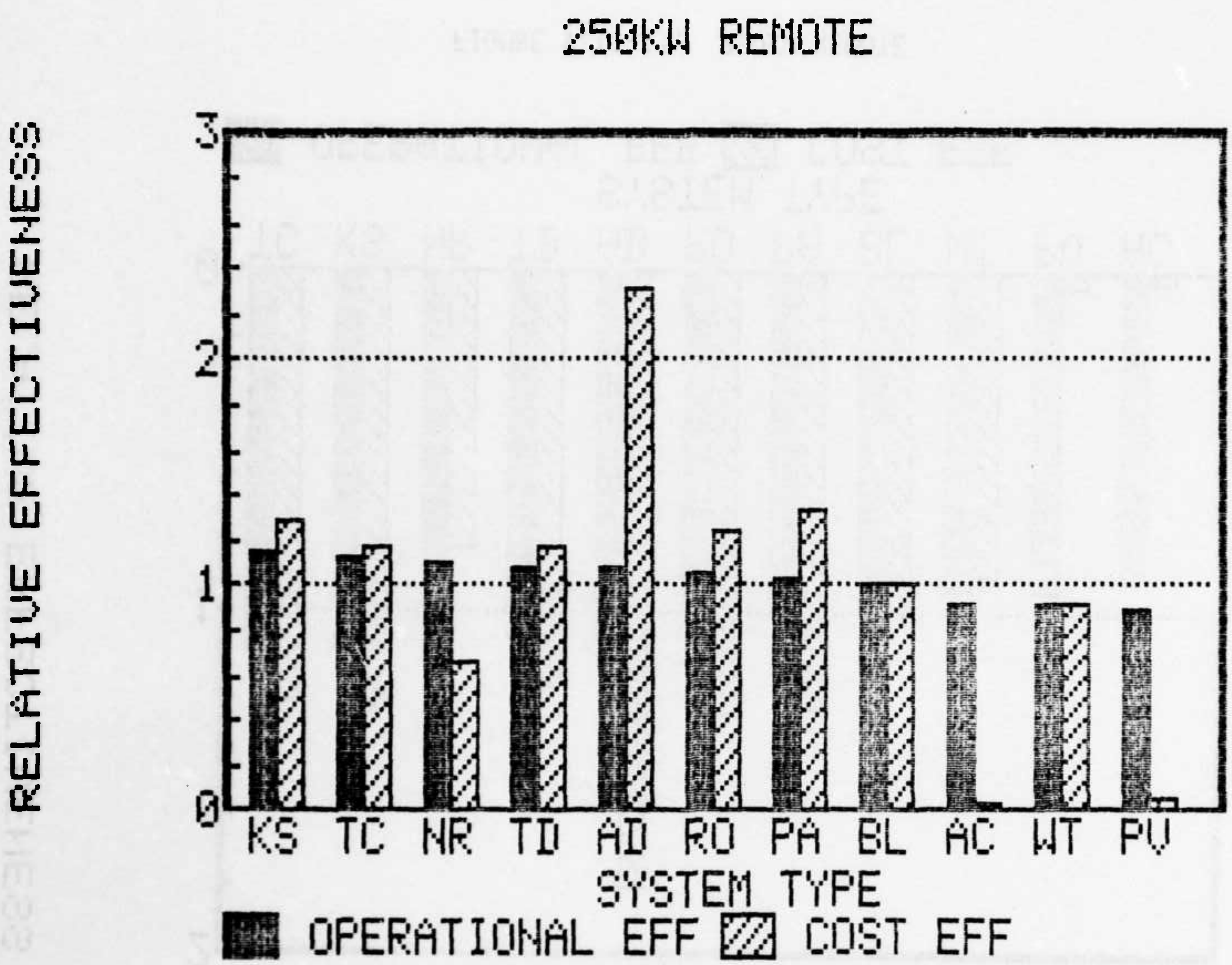

FIGURE VIII-12: 250KW REMOTE

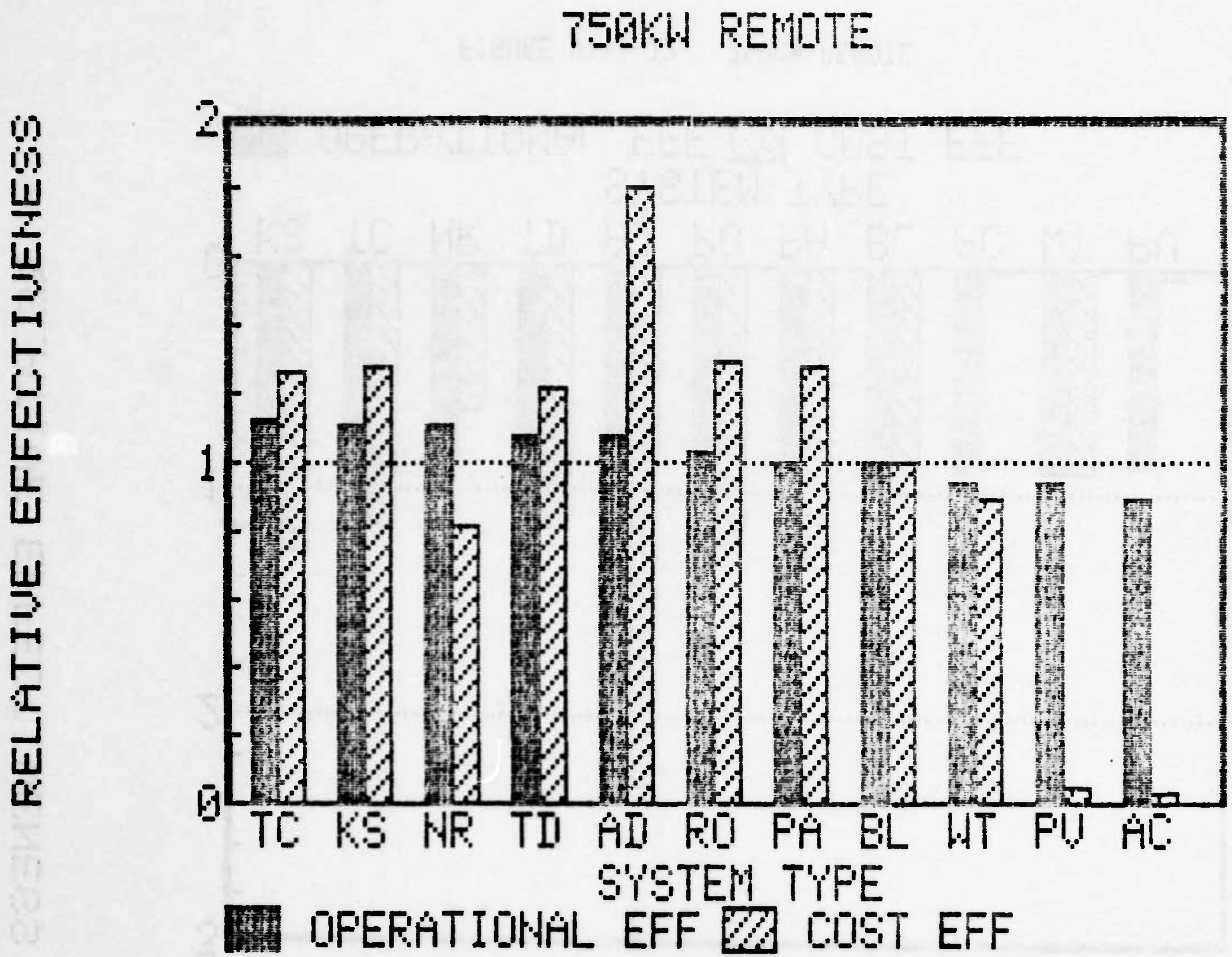

FIGURE VIII-13: 750KW REMOTE

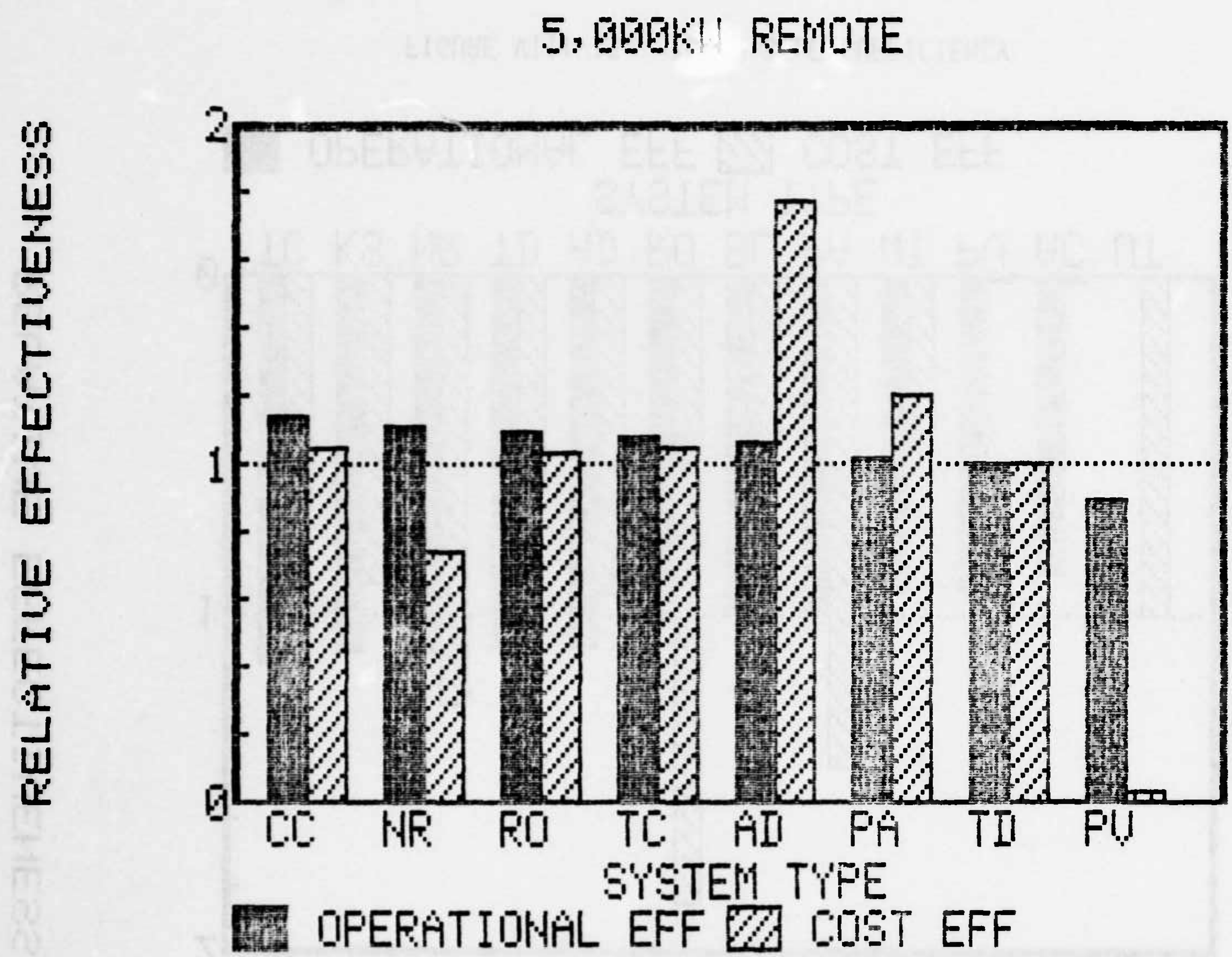

FIGURE VIII-14: 5,000KW REMOTE

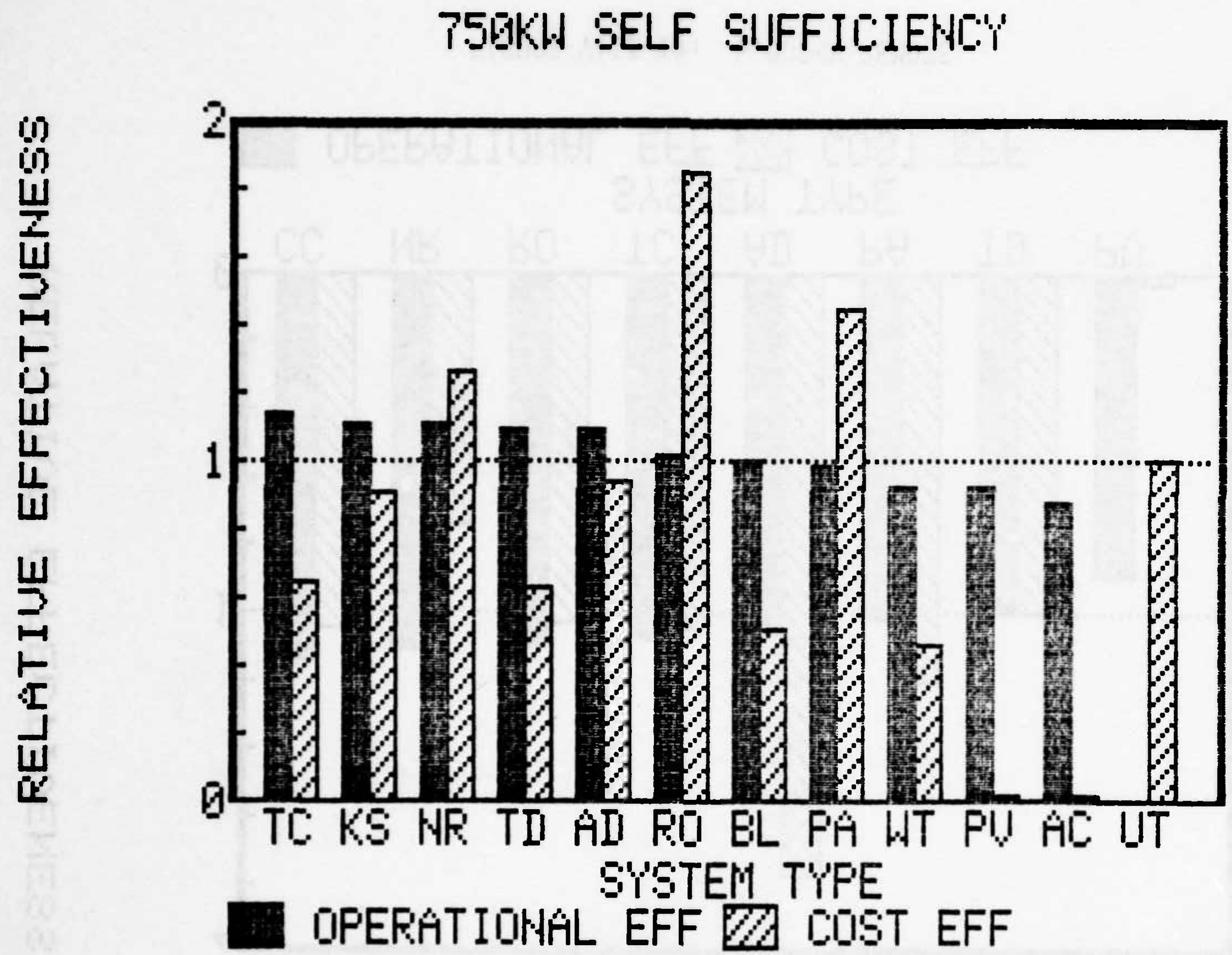

FIGURE VIII-15: 750KW SELF SUFFICIENCY

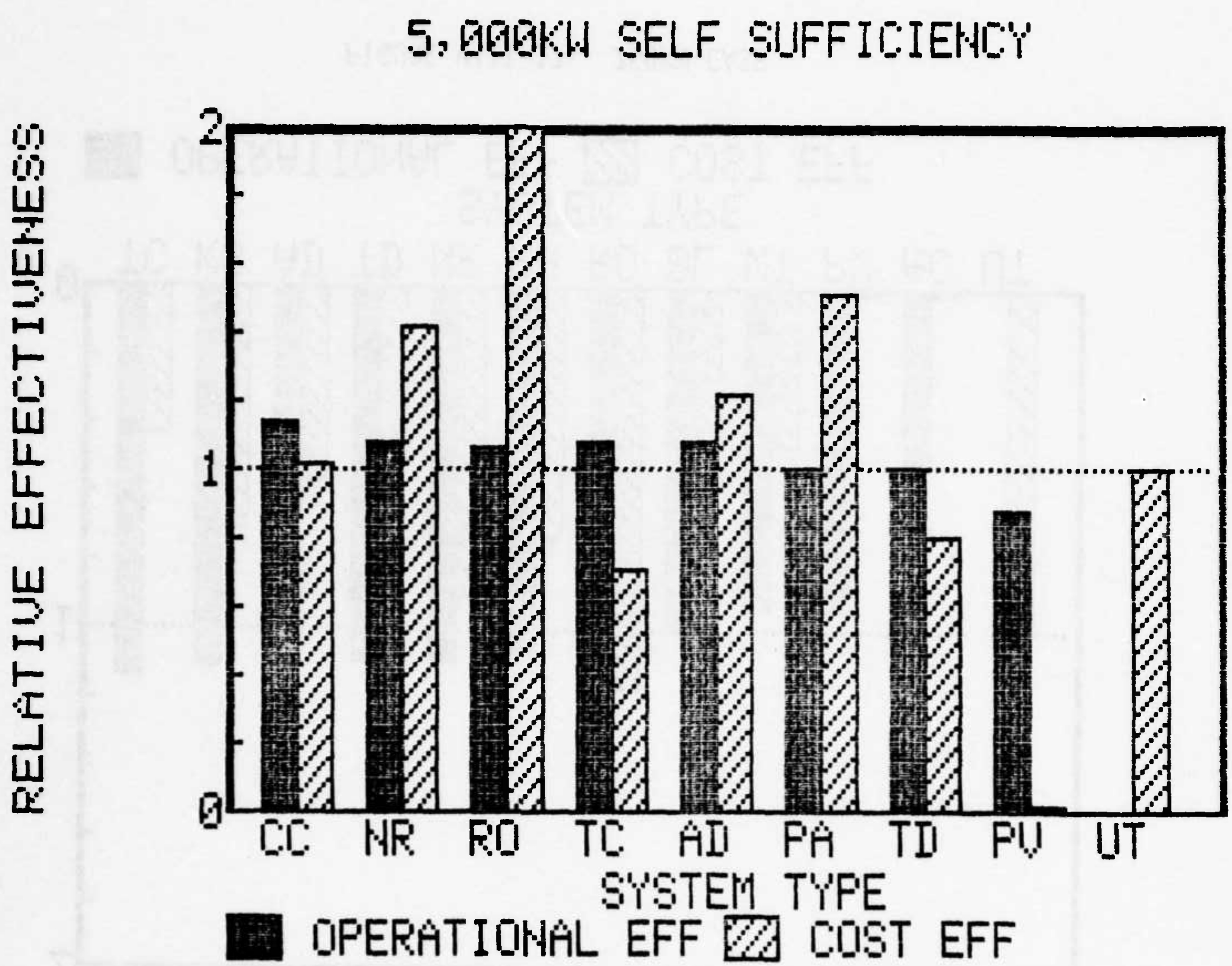

FIGURE VIII-16: 5,000KW SELF SUFFICIENCY

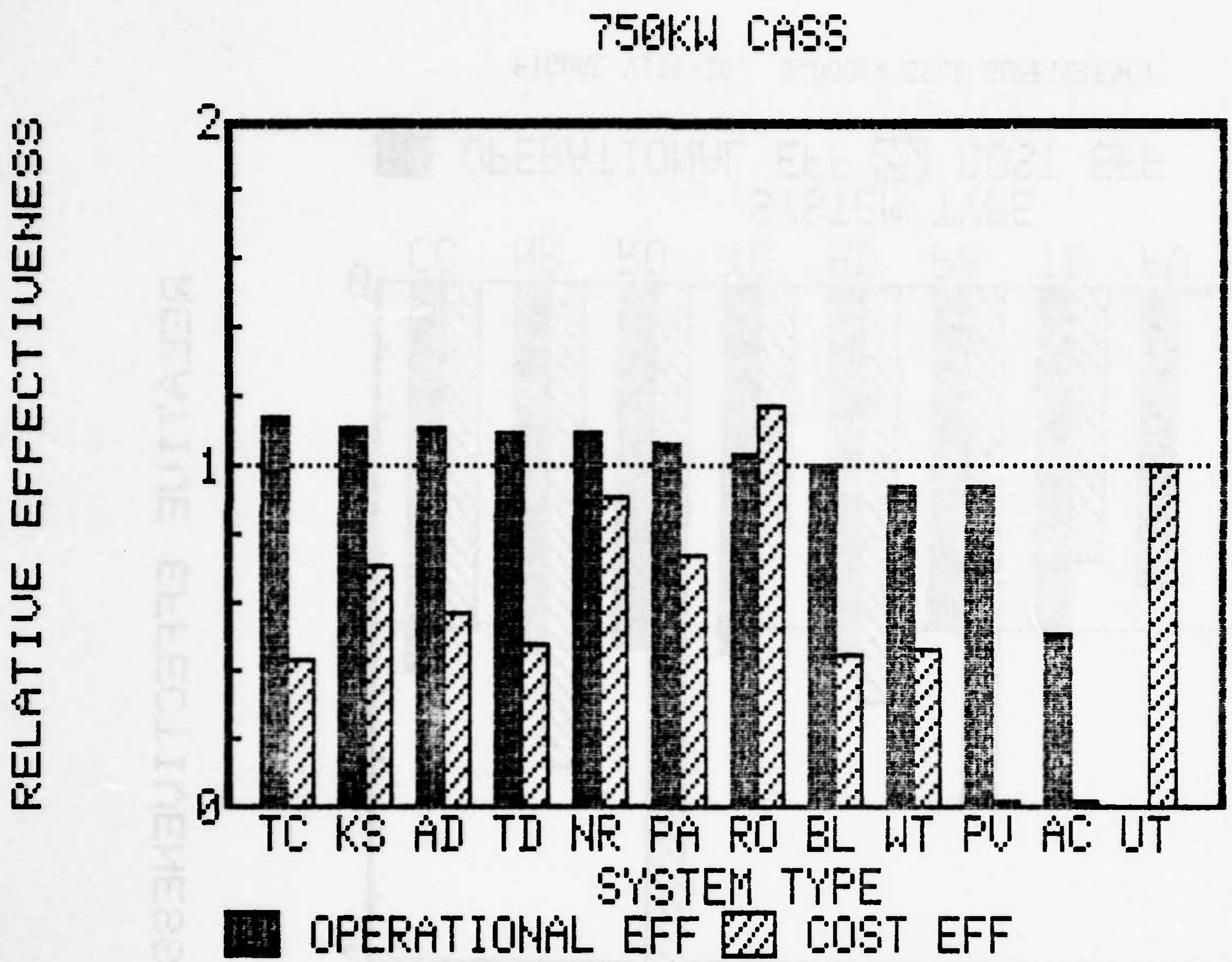

FIGURE VIII-17: 750KW CASS

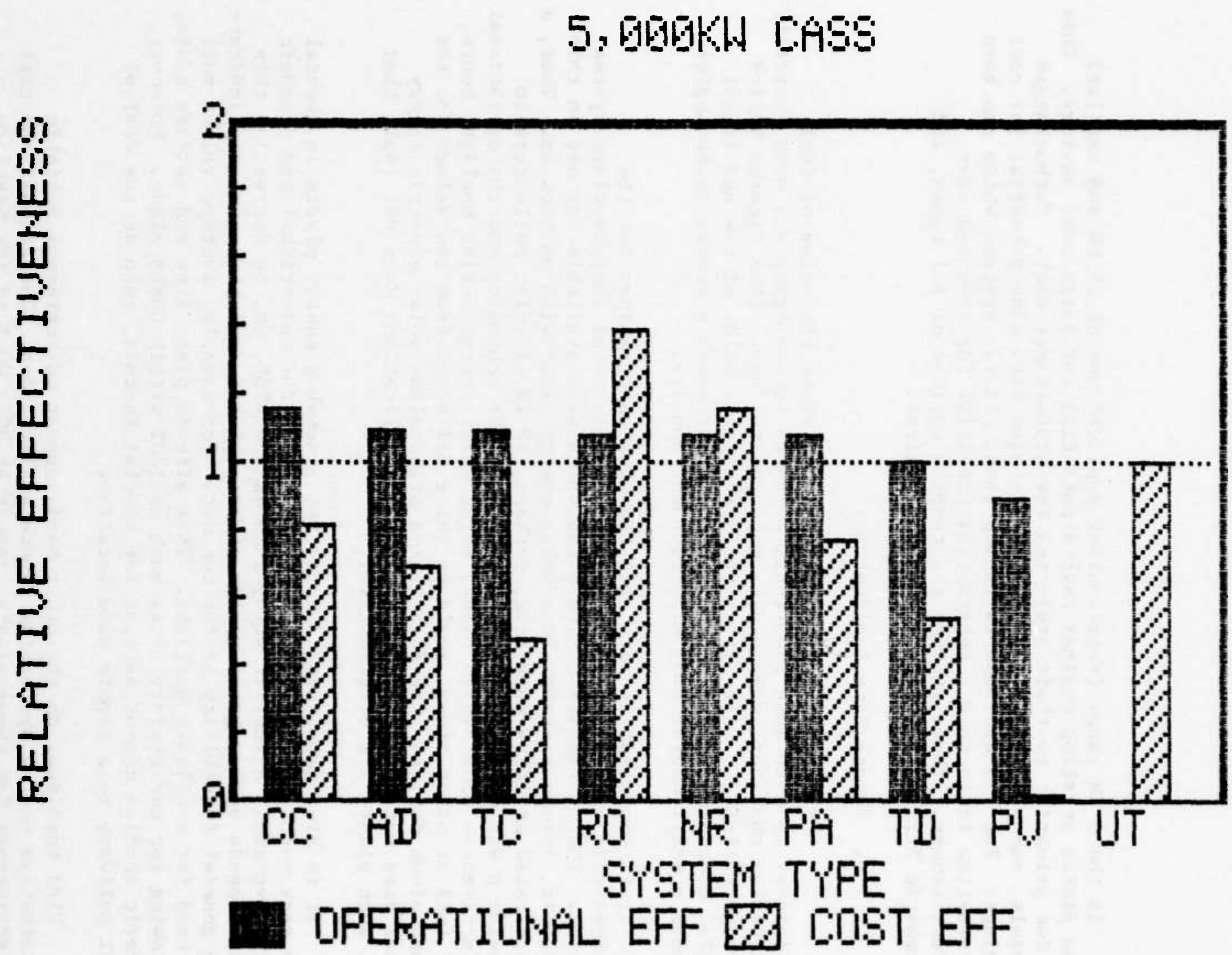

FIGURE VIII-18: 5,000KW CASS

In the 5 kW range (representing applications of 25 kW and smaller) free piston Stirling engines have a potential for large cost savings. This is due primarily to their projected low procurement cost. Turbocharged diesels, and phosphoric acid fuel cells also show some potential for cost savings. For 750 and 5000 kW backup power plants, systems which can burn alternative fuels show a substantial potential for enhanced cost effectiveness. These include gas turbine engines of all types, and kinematic Stirling engines in available sizes.

c. Remote Site Applications

For remote site applications, where the value of fuel efficiency is much more important, advanced technologies are more generally attractive than for emergency/backup applications. (See Figures VIII-9 through VIII-14). Once again, the operational value of the new fossil fueled technologies is marginal, while the renewable energy technologies impose a small operational effectiveness penalty.

It is important to note that the poor cost ratings for the photovoltaic systems are primarily a consequence of inappropriate system design. The statistics of the ATES, which were available for use in this analysis, assume a stand-alone solar energy plant with no back up. Thus, a plant rated at 10 kW must have, perhaps, 50 kW of solar collectors to provide power during non-sunlight hours. The economics and the operational effectiveness of a hybrid plant, using solar energy during sunlight hours, and fuel at other times, would be quite different from the values for the stand alone design. The fact that a stand-alone solar electric energy plant does not appear effective in USAF applications does not imply that all such plants are unattractive.

It is also important to note that renewable energy plants in general are very much site dependent in their design for operational and economic effectiveness. A generic study such as the ATES, and by derivation this one, depends upon a great number of assumptions, and thus can only indicate the general feasibility of the concept. For example, average values must be used for available sunlight. This affects plant size and storage costs, allowing for uncertainty of as much as 100% within CONUS alone. Moreover, generic studies cannot account for special factors, such as the cost of fuel delivery to a remote site location.

Wind turbines, on the other hand, appear to represent a viable alternative energy system for remote applications. Operational and cost effectiveness for these plants project at 80 - 90 % of the baseline, a measure that is within the margin of precision for the study. In especially favorable locations, it seems likely that wind turbines could match or exceed DED systems. The question of electromagnetic interference generated by large oscillators, needs to be considered, however. According to the data in the ATES, there exists no significant difference between horizontal axis and vertical axis systems. Therefore, results for these alternatives were combined into a single statistic.

For small energy systems, i.e. 1-25 kW, as represented by 5 kW, free piston Stirling engines show the greatest potential for improvements to the baseline. Phosphoric acid fuel cells, turbocharged diesel engines and kinematic Stirling engines are all equally good choices within the limits of precision of the study. The principal favorable characteristic in each case is increased fuel efficiency.

Phosphoric acid fuel cells, kinematic Stirling engines and turbocharged diesels are good alternatives in intermediate sizes as well, i.e. from 26 - 175 kW, as represented by 60 and 100 kW systems. Beginning with the 250 kW size range and increasingly for larger sizes, adiabatic diesel engines become the system of choice. The other candidate systems remain competitive with conventional DED systems in all sizes.

In summary, all of the advanced technology, fossil fuel systems represent operationally effective alternatives to DED remote site power plants by the year 2000. There appear to be no strong operational reasons for a general conversion to advanced technology plants. There does seem to be a sound basis for anticipating substantial cost benefits from advanced technology power plants, however, notably Stirling cycle engines and fuel cells in all sizes, and adiabatic diesels in large sizes. These potential benefits are not tied to any scenario of fuel scarcity, because the economic projections assumed no general escalation of fuel costs.

d. Base Self Sufficiency

The current method of purchasing power generated across the fence from the domestic utility grid is probably inconsistent with real base self sufficiency. As shown by Figures VIII-15 and VIII-16, current systems burning liquid petroleum fuels are not cost competitive with utility power at $0.05 per kWH, thus base self sufficiency would require that a premium price be paid for that operational capability.

Systems fueled by natural gas, however, demonstrate a real potential to provide a power production capability at a price which is competitive with utility power. In larger plants (5000 kW), phosphoric acid fuel cells and adiabatic diesel engines are additional candidates. It should be noted, however, that the economic comparison does not include the cost of the fuel storage and handling capital investment which would seem to be a prerequisite to long-term self sufficiency.

e. CASS

The generation of power strictly for aircraft support might be seen as a partial step toward self sufficiency, i.e. sufficiency for critical mission functions. If power is generated full time, and applied toward aircraft support as needed, and toward other applications otherwise, then the statistics for base self sufficiency apply. If CASS systems were operated on some other duty cycle, say one third time in support of flightline maintenance on a single shift, then the statistics in figures VIII-17 and VIII-18 would apply.

The analysis indicates that there is little to be gained from this conceptual alternative.

f. Summary of Results

Figure VIII-19 presents a summary table of projected cost and operational effectiveness for the technologies and applications considered. None of the advanced technologies show an outstanding potential to enhance the operational effectiveness of facilities electric generating systems.

The balance of the results are the inverse of those for MEP applications, where enhanced mission effectiveness could be achieved using advanced technologies at a competitive cost. For FEGS systems, enhanced cost effectiveness may be achievable with no loss in mission effectiveness.

A number of systems show a large potential for cost savings in FEGS applications when using natural gas as a fuel. These cost advantages would also accrue to other technologies, if designed to burn natural gas. The advantages, however, disappear if natural gas prices escalate to a cost competitive with refined petroleum products.

Those systems which should be generally competitive with the baseline are found in Column C. Most noteworthy is the fact that wind turbine systems fell in this category. This is a highly site dependent technology. Therefore this general analysis would indicate that wind turbines are worthy of detailed consideration for remote site applications where favorable site factors exist.

	A COST & PERF >1.2 BL	B PERF >0.8 BL COST >1.2 BL	C COST & PERF >0.8 BL
BACKUP			
5KW	FP	TD,PA	KS
60KW			KS
100KW			KS
250KW			RO,NR,KS
750KW		RO,NR,KS	
5000KW		RO,NR,CC	AD,PA,TD
REMOTE			
5KW	FP	PA,TD,KS	SP,WT
60KW		KS,PA,TD	WT
100KW		PA,KS	TC,TD,WT
250KW		AD,PA,KS,RO	TD,TD,WT
750KW		AS,RO,KS,PA,TC	TD,WT
5000KW		AD,PA	TC,RO,TD,CC
BASE SELF-SUFFICIENCY			
750KW		RO,PA,NR	KS,AD
5000KW		NR,PA	CC
CASS			
750KW		RO	NR
5000KW		RO	NR

AD = ADIABATIC DIESEL
CC = CLOSED CYCLE GAS TURBINE
WT = WIND TURBINE
SP = SOLID POLYMER FUEL CELL
TD = TURBO-CHARGED DIESEL
PA = PHOSPHORIC ACID FUEL CELL
RO = RECUPERATED OPEN CYCLE TURBINE
NR = NON-RECUPERATED OPEN CYCLE TURBINE
TC = TURBO-COMPOUNDED DIESEL

FIGURE VIII-19: SUMMARY OF RESULTS

IX. Interpretation of Results, Conclusions and Recommendations

A. Introduction

It was the objective of this research to determine the overall potential of specified advanced electrical power generation technologies to satisfy future USAF needs. The purpose of research was to identify areas where USAF sponsored R&D might contribute to the realization of effective advanced technology systems in USAF applications by the year 2000.

Interviews and surveys with USAF MEP and FEGS users and managers provided, for the first time, a substantial data base on requirements for electrical power systems. The efforts of the technical subcontractors provided updated information on the technologies of interest, and characterized potential research which might contribute to USAF goals.

The analytical portion of this study has focussed on the use of statistical information generated on technologies and applications. This information on requirements was compared with updated projections of advanced technologies' characteristics in several ways to develop an understanding of technologies' potential for operational and cost effectiveness in the most common USAF support missions.

Most innovative was the development and use of the Multiple Attribute Decision Model (MADM) to project the operational effectiveness of advanced technologies' systems in USAF applications. The research team also forecast a simple cost comparison using life cycle costing methods.

As noted in the description of the research approach, (Chapter III.A.2), the research team conducted field interviews, in part, to provide a basis for the interpretation of the results of the quantitative survey. One disadvantage of a statistical approach to problem solving is the ambiguity of results taken out of context. This concluding chapter attempts to replace the statistical results into their context, and to consider the needs and potential for advanced technology development for USAF MEP and FEGS applications from this holistic perspective.

The following sections proceed to recapitulate and interpret the findings reported in the previous chapters. They narrow down the alternatives by considering first the potential of advanced technologies to enhance the operational effectiveness of USAF electrical power support systems. Cost considerations then narrow the field of candidate technologies. The results of field interviews and comments are then consiidered, and the technical subcontractors research recommendations are compared to the need. Finally, recommendations are made which integrate all of these factors.

B. Candidate Technologies Based on MADM Projections of Operational Effectiveness

The use of the multiple attribute decision methodology and model revealed the following:

1. For fixed facilities applications:

a. Fuel burning, advanced technology systems can be equally mission effective with current electric energy plants.

b. No advanced technology system studied offers a substantial improvement in operational effectiveness over current, mainly diesel engine driven (DED) systems.

c. The major deficiencies which must be overcome to increase operational effectiveness for the advanced technology systems are those of reliability, operability, maintainability, and system lifetime. These deficiencies are not the sort which are susceptible to R&D at this stage. Rather, they are of the sort which must be overcome through increasing experience with fielded systems.

d. Some of the major advantages of advanced technologies, e.g. mobility, size and weight, are of little value to facilities applications. Their potential for increased fuel efficiency, which is valuable, is balanced out by the risk characteristics associated with innovation.

e. Stand-alone (i.e non grid-connected, non-hybrid) photovoltaic power plants of any design, fall below the operational standards of current DED systems. (Because this was a generic analysis, however, and renewable energy systems are extremely site dependent, photovoltaic systems will not necessarily fall below current standards in any given site and application).

f. The analysis did not address hybrid energy plants, which combine local renewable resources with fuel burning systems.

2. For mobile electric power applications:

a. Several advanced technologies have the potential to increase the operational effectiveness of USAF support systems by the year 2000:

1) For flightline support, phosphoric acid fuel cells, kinematic Stirling cycle engines, advanced gas turbines, and turbocharged diesel engines all have a potential for enhanced operational effectiveness.

2) For TACS support, phosphoric acid fuel cells and kinematic Stirling cycle engines can enhance operational effectiveness.

3) A broad range of technologies offer potential enhancement for large (750 kW) mobile systems. These include

turbocompound, turbocharged, and adiabatic diesels, kinematic Stirlings, phosphoric acid fuel cells and advanced gas turbine engines, both regenerative and non-regenerative.

4) There also exists a substantial opportunity for enhanced operational effectiveness for small generator sets using free piston Stirlings, phosphoric acid fuel cells, kinematic Stirlings, turbocharhed diesels or solid polymer fuel cells.

5) For tactical utility generators larger than 25 kW, the potential for operational improvement increases with system size. At the 60 kW level, kinematic Stirlings and phosphoric acid fuel cells offer marginal improvement. The advanced technology alternatives increase in value to the 250 kW level, where all systems considered indicate a potential for enhanced operational effectiveness.

C. Further Selection of Technologies Based on Projected Cost Effectiveness

A consideration of projected, comparative cost effectiveness permits a sharper focus on system potentials:

1. For fixed facilities applications:

a. In emergency/backup and base self-sufficiency FEGS applications, current standards of operational effectiveness can be maintained with potential cost savings for very small and very large systems:

1) Free piston Stirlings, turbocharged diesels and phosphoric acid fuel cells have a potential to decrease costs for small systems.

2) Systems which can utilize natural gas as a fuel have a potential to reduce life cycle costs for large systems, increasing with system size. The potential is largest for regenerative gas turbine systems.

b. For remote site applications, there exists a great potential for cost savings through new technology applications:

1) For small plants, free piston Stirling engines and phosphoric acid fuel cells offer the greatest cost savings potential.

2) For intermediate sized applications, phosphoric acid fuel cells and kinematic Stirling engines have the greatest potential.

3) Turbocharged diesel engines also have a potential to reduce costs in small and medium sizes.

4) Adiabatic diesel engines have the greatest potential to

reduce costs in large and very large systems.

5) Phosphoric acid fuel cells and kinematic Stirlings also have cost effectiveness potentials in these sizes.

6) The concept of a dedicated fixed facility CASS does not seem to offer any particular operational or cost advantages in comparison with overall base self sufficiency.

2. For MEP applications:

a. The enhanced performance potential which advanced technologies offer often carries with it a higher price tag. The principal trade off is between system procurement cost and enhanced fuel efficiency, and thus lower fuel cost. Since most MEP systems have a low duty cycle in peacetime, this means that the extra, up-front investment in fuel efficiency will not typically pay off.

b. A few advanced technologies offer a potential for enhancing both operational and cost effectiveness in MEP applications. These are:

1) Free piston Stirling engines and turbocharged diesel engines in small sizes.

2) Phosphoric acid fuel cells in small to mid-range applications.

3) Kinematic Stirling engines in mid-range applications.

4) Regenerative gas turbines in large applications.

D. Additional Considerations

Knowledge gained from interviews and surveys in the field support the emphasis of the following points as interpretations, elaborations, or modifications to the quantitative operational and cost effectiveness projections.

1. Operational Factors

a. For TACS generators, reliability, fuel consumption, mobility and emissions are of real operational concern. These factors are important for the units equipped with the A/E 24U-8 power plant (MEP 404). They are vital for the TACPs equipped with the MEP 25 and MEP 26 (1.5 and 3 kW DC generators). Current technologies require a trade off between reliability and fuel consumption on the one hand, and mobility on the other. New technology systems which are light weight and portable, yet fuel efficient would enhance the survivability and mission effectiveness of these using units, upon whom thousands of lives depend in combat situations.

b. For flightline generators, fuel efficiency, noise, and mobility are the operational variables of concern to system users. Fuel efficiency is important because of the operational impacts of stopping to refuel. The noise level of current support generators is such that it degrades operational effectiveness, impeding communication between crew members. Mobility for deployment operations is a continuing concern. Any design which is simpler and faster to load and unload for airlift would be considered a benefit to operational effectiveness.

c. Quality and stability of power output are of continuing and increasing concern for flightline avionics and other electronics support. Even small power fluctuations can "crash" complex maintenence programs, lasting many hours, which must then be reinitiated to complete. This is a complex problem, whose principal variables are not necessarily technology dependent. One design factor is system sizing to match the load. One problem is that new aircraft and new generation avionics change the load to be supported. Power conditioning and system design tools are available to match any of the advanced technologies to the power requirements imposed by this application. However, trade-off analysis and careful planning will be required in the development of new technology designs.

d. Mobility, fuel efficiency and emissions are also important for utility generators in all sizes. Because their mission support role is less direct than the other applications discussed here, the need is less urgent. In other words, it is often possible to get the job done with reduced utility generator support, albeit with more difficulty and less efficiency. Without the communications and electronics and maintenance support, however, operations may cease or be extremely degraded. However, lessons learned in providing better generators for combat support can and should be transferred to generators for combat service support.

e. For emergency/backup systems, the principal concern is reliability. This means assurance that the backup system will come on line whenever needed. The current, DED technologies appear to be wholly adequate to the job from a technological standpoint.

f. There is an increasing demand for back-up power for computer and other electronics support in fixed facilities. For these applications the demand for stability and quality of power output parallels that of mobile electronics support generators.

2. Cost factors

It is difficult to make generic statements regarding comparative costs for engine generators in both FEGS and MEP applications. The systems studied here sometimes represented a range of system sizes, (e.g. 5 kW MEP for 1 - 20 kW systems). The life cycle cost analyses undertaken as part of this research can only serve as a guide, because their meaning is inherently abstract, due to the level of aggregation of information. (This is the reason that a more precise methodology would be meaningless).

For FEGS, each installation is unique. There are no standard types, sizes, or models of equipment. There are no standard duty cycles. The price and availability of fuel and electricity varys from location to location. For these reasons, any precise cost projections must be site and application dependent.

Of greater concern for both FEGS and MEP systems, is the problem of peacetime versus wartime duty cycles. As discussed in Section VIII.A., Back-up systems have the inescapable characteristic of being purchased as insurance against events that the purchaser hopes will not occur. Similarly, mobile plants achieve their greatest use, for most applications, only during exercises or wartime.

The question is whether to emphasize the cost criteria of normalcy which is more likely, or to optimize costs for emergency or wartime use, which is less likely, but more crucial. This is a pertinent question with operational consequences because the trade-off for cost savings during peacetime is increased fuel consumption and thus increased logistics burden and decreased self sufficiency in an emergency situation. The compromise used in this report, to assume a one-eighth duty cycle was a reasonable one, based on interviews with system managers. There seems to be no general USAF policy for planning in this area.

Cost estimation is more meaningful for MEP applications in that generator sets are standardized and cost elements are well known and available. Even so, costs often depend on factors such as purchase quantity. Moreover, the duty cycle for each individual generator set is unique. Average values are misleading. An arbitrary one-eighth duty cycle may represent one unit run 50 % of the time and three sitting idle and uncrated. It may represent four units run full time during infrequent exercises. There does appear to be some opportunity for cost savings through duty cycle and inventory management in some applications.

3. Supportability Factors

The research team received the distinct impression during the course of field interviews with perhaps a hundred MEP operators, maintainers and managers that design issues as they relate to system maintainability and supportability were equally or more important than technology concept issues. Such mundane questions as fuel tank size and location, the choice of electronic vs. mechanical control systems, the placement and design of power cords, interchangeability of components, and a myriad of similar issues were of a high level of concern to system users and maintainers.

Most of the issues involved applications engineering, i.e. designing the system for optimal performance in its intended use. These issues are equally important to new technology plants as to current technology ones. Their importance underlines the necessity for developmental programs aimed at implementing advanced technologies in designs which are appropriate for USAF applications. So that the oversights of the past might be avoided, we strongly recommend that future development programs by USAF, involve using units and maintenance professionals from the earliest steps of the development process. This is especially true for specialized systems such as flightline, electronics support and BARE BASE support generators.

The major thrust of the comments received in this area has little to do with specific technologies, and much to do with management and planning. The major conclusion to be drawn here is that greater attention is needed to ILS elements whatever the technology base. The major engineering conclusion is that detailed system design must take logistics factors into account whatever the basic design concept. The comments received by MEP and FEGS users during this research indicate that there is at least as much opportunity for operational and cost effectiveness enhancement through greater attention to ILS elements in system design, as there is through the exploitation of advanced technologies.

E. Research Opportunities

Figure IX-1 presents a summary comparison of the statistical potential of new technologies to enhance USAF operational and cost effectiveness with the costs of recommended research. Combinations without clear cost and performance benefits have been eliminated. The inventories presented represent approximate purchases which might be made over a twenty year lifetime and procurement cycle. Somewhat higher inventories than currant ones were selected for the 100 kW tactical precise and 750 kW prime power systems, to reflect possible, higher future inventories of these systems.

R&D figures are combined for the 60 and 100 kW kinematic Stirling systems because a single research effort would be responsive to the three system needs. Also, the assignment of phosphoric acid fuel cells against the current TACS application and the kinematic Stirling against the other three 60 and 100 kW applications is somewhat arbitrary. Actually either technology could satisfy any of the four applications.

An examination of Figure IX-1 indicates that the costs of the research programs recommended by the technical subcontractors appear to be reasonable in comparison with the potential benefits to USAF of successful research. Some cautions need to kept in mind when interpreting the cost comparisons in Figure IX-1.

The general caution is the impact of imprecision as discussed in section C.2 above. Presumably, such assumptions as made by the research team will act similarly on all systems and tend to cancel out in a comparative use of the cost data. Secondly, is the issue of fuel costs. The cost estimates made by the research team assumed no net change in the real cost of fuel over a thirty-six year period extending to 2020. If real fuel costs decline over the period, the impact would be to favor the baseline technologies. If real fuel costs rise over the period, the impact would be to favor the advanced technologies. The net impact of changing fuel costs is improved by the low duty cycle for MEP equipment under a peacetime scenario.

A. Type	5 kW	TACS	60 kW FL	60 kW TU	100 kW TP	750 kW
B. Inventory	4,500	1,000	4,000	2,250	200	100
C. Acquisition Cost, BL	$ 8 K	$ 95 K	$ 23 K	$ 23 K	$ 65 K	$ 450 K
D. LC Cost, Base Line	$ 27 K	$ 666 K	$ 208 K	$ 189 K	$ 345 K	$ 2,300 K
E. Advanced Technology	FP	PA	KS	KS	KS	RO
F. Acquisition Cost, AT	$ 4.5 K	$ 42 K	$ 30 K	$ 30 K	$ 50 K	$ 420 K
G. LC Cost Adv. Tech.	$ 13.5 K	$ 251 K	$ 180 K	$ 180 K	$ 292 K	$ 2,100 K
H. Acq. Cost Benefit B*(C-F)	$ 16 M	$ 53 M	($ 28 M)	($ 16 M)	$ 3 M	$ 3 M
I. LC Cost Benefit B*(D-G)	$ 61 M	$415 M	$112 M	$ 20 M	$ 11 M	$ 20 M
J. Cost of Research	$ 3.3 M	$ 14 M	>>>	$ 25 M	<<<	$ 10 M
K. Operational Effect. Ratio	2.2	1.2	1.6	1.2	1.7	1.2
L. Rsch/Benefit Ratio	18:1	30:1	>>>	6:1	<<<	2:1

Figure IX-1. Summary Comparison Chart

Finally, the cost comparison is based on current systems, and does not take into account intermediate generations which might reduce (or increase) current costs. We beleve that all of the baseline systems used in Figure IX-1 are low cost systems except for the TACS baseline, which is known to be a high cost power plant. There are current plans to replace this unit with a lower cost system.

A conservative approach for the mid-sized units, i.e. 60 kW and 100 kW, would be to consider them as a group. The baseline used for flightline applications was the extremely cost effective MEP 357A. This may be taken to represent an asymptopic value for the current technology. If we compute the cost savings potential for TACS applications to the asymptopic value instead of the current value, then the overall life cycle cost benefit potential for 60 kW and 100 kW USAF units is $ 171 million. If USAF supported simultaneous research and development programs at the levels recommended by the technical subcontractors, then a two-pronged program to develop phosphoric acid fuel cells and kinematic Stirling engines for mid-sized MEP applications would cost about $ 40 million, a net savings to research investment ratio of 4.3:1.

Research into alternative electrolyte acid fuel cells does not seem to present any advantage to USAF at this time. Certainly USAF should monitor such research and reconsider this alternative as the state of the art advances or as needs change.

The research costs identified by the research team do not include all potential research costs. In particular, additional funds for prototype fabrication would be needed for the phosphoric acid fuel cell systems. A smaller level of additional funds would be necessary for kinematic Stirling engine to generator matching as discussed in Chapter VII, Section H. Funds would be needed for field testing of all units.

Of course, all R&D funding need not come from USAF resources, even if a full program were undertaken. The other military services have similar MEP needs. The Department of Energy sponsors related programs, though few that are directly MEP related. Cost sharing by manufacturer/developers is a proven strategy.

It is also true that USAF facilities applications stand to benefit from successful research. Aggregating over emergency/backup inventories, using average FEGS sizes, BCE holdings include 750 small generators which would benefit from free piston Stirling research, 150 large units which would benefit from regenerative open cycle turbine development, and 8,000 mid-sized systems which could benefit from fuel cell and kinematic Stirling engine systems. The actual scope of cost benefits to be realized depends upon the duty cycle for these units. A policy decision to pursue base self sufficiency would dramatically escalate the advantages to be gained from advanced technologies research and development because of the large fuel savings potential of the advanced technology systems.

The proposed research and development programs are not high risk ones. Preliminary work in all four technology areas has indicated the feasibility of the technology concepts. Prototype systems exist for all four technologies in similar size ranges. The U.S. Army has already programmed procurement of phosphoric acid fuel cells in 1.5 and 3 kW sizes for FY 1987 and FY 1988. These systems should be examined by USAF for use by TACPs and MAC CCTs, although their methanol fuel may be a drawback in comparison to the system studied here.

Nonetheless, a significant amount of engineering development work remains to be done in all four recommended research areas. If performed sequentially, the research projects and tasks would consume ten years for kinematic Stirling and phosphoric acid fuel cell initiatives. Regenerative open cycle turbine work for a 750 kW mobile system would require six years. The 5 kW free piston Stirling engine program would require four years. When combined with normal project lead times, this means that IOC dates of 1990 for small free piston Stirlings, 1992-1995 for 750 kW regenerative gas turbines, and 1995-2000 for mid-sized fuel cells and/or kinematic Stirling engine driven generators are reasonable. An escalated schedule would be feasible if resources were made available.

Figure IX-2 presents a summary of the potential for research and development to enhance USAF electrical generating systems' effectiveness. The payoff ratio represents the projected life cycle benefits for a generation of USAF MEP systems, divided by the projected cost of research. Given the nature of research and of cost analysis, it would be adviseable to discount this value by some percentage to represent the risk of projection and that of over-runs in research, due to unforseen problems. The research team believes that an appropriate and conservative expected payoff ratio would be half the indicated value for the single technology programs and three quarters the indicated value for the two technology program.

The column labelled "Operational Payoff" gives the ratio of operational effectiveness for the advanced technology compared to the current system as projected by the MADM analysis. These benefits are in addition to any cost benefits. In the case of the mid sized units, the operational payoff of the most valuable application, i.e. flightline power support, has been indicated.

Program Area	Program Cost	Duration	Cost Ratio	Payoff ($)	Operational Payoff
Small Free Piston	$ 3.3 M	3 years	18:1	$ 60 M	2.2:1
Mid sized Fuel Cell & Kinematic Stirling	$40 M	10 years	6:1	$171 M	1.6:1
750 kW Regenerative Gas Turbine	$10 M	6 years	2:1	$ 20 M	1.2:1

Figure IX-2. R&D Program Summary

F. Findings and Recommendations - Mobile Electric Power Systems

1. There exists a positive potential for USAF to realize both cost and operational effectiveness improvements in mobile electric power mission support through the introduction of advanced technology systems in the 1990-2000 time-frame.

2. The highest potential payoff is in areas where electrical generator support is most clearly mission related. These areas are:

a. Small (1-5 kW) generators in support of TACPs and MAC CCTs.

b. Medium sized (45 to 100 kW) generators in support of flightline and electronics missions.

c. Large (750 kW) generators in support of BARE BASE and rapid deployment missions.

Utility generators will also stand to benefit from advanced technology development, and will contribute to the overall cost benefits to be realized.

3. Free piston Stirling engine driven generators have the highest potential to meet small MEP applications. Not only does this technology score highest for projected cost and operational effectiveness, its characteristics of compactness, low weight, fuel efficiency and quiet operation are especially well suited to its most important mission applications.

4. Kinematic Stirling engines and phosphoric acid fuel cells have the highest potential to meet mid-sized flightline and electronics support applications. Increased fuel efficiency and quieter operation are important characteristics of these technologies. Research and development is necessary to realize light weight systems of proven reliability.

5. Regenerative open cycle gas turbines have the highest overall

potential to meet USAF requirements for large mobile power plants in support of rapid deployment. Other technologies have higher operational effectiveness potential, but are not cost competitive at low duty cycles.

6. USAF will gain from the implementation of research and development programs in these three areas. The benefits to be derived are enhanced operational effectiveness and cost savings totalling over $250 million, (about $165 million if discounted for risk), over system lifetimes.

7. The R&D opportunity with the best potential for payoff (18:1 or 9:1 incorporating an estimated risk factor), the smallest investment ($3.3 million), and the shortest lead time (IOC around 1990) is the development of small free piston Stirling engine driven generators.

8. The R&D opportunity with the largest potential for general impact on USAF missions is the parallel development of fuel cells and kinematic Stirling cycle engine driven generators for mid-sized applications. The payoff potential is approximately 6:1, or 4:1 discounted for risk, with an investment of $40 million over a ten year period, leading to IOC between 1995 and 2000. Applications include flightline and electronics support as well as utility applications.

9. An R&D opportunity also exists to enhance the effectiveness of large mobile generators in support of rapid deployment. An investment of $10 million has a payoff potential of approximately 2:1 (1:1 discounted for risk), leading to fielded systems between 1992 and 1995. This payoff assumes an inventory increase to 100 systems. It is also based upon a low (one-eighth) duty cycle. Higher duty cycles would increase the potential payoff and also the competitive attractiveness of other, more operationally effective advanced technologies.

10. There exists a great potential and a great need to enhance the operational and cost effectiveness of both current and advanced technology MEP systems through enhance planning and management in the area of integrated logistics support and in duty cycle management.

11. By its nature, this state of the art and applications assessment must be updated regularly to remain a valid research management tool. We recommend a triannual review or an appropriate schedule.

G. Findings and Recommendations - Facilities Energy Generating Systems

1. The major use for FEGS is in emergency/backup applications. Current technologies are operationally effective in these applications. Advanced technology systems offer only marginal improvements.

2. Current technologies are also operationally effective in remote site applications, however, advanced technology systems offer substantial potential for cost savings. There are good candidate systems in each size range.

3. Given the lack of potential for any notable enhancement of operational effectiveness, the diversity of technologies which can result in enhanced cost effectiveness, and the limited number of USAF remote site applications, no major impetus seems to exist for undertaking an autonomous USAF technologies development program for any of the fuel burning technologies.

4. Facilities applications can benefit from the results of any MEP applications R&D which USAF should choose to undertake. It would be wise and reasonable for facilities engineering programs to contribute to and participate in MEP development programs to encourage and realize technology transfer. The greatest opportunities are in small and large generators, where the potential for cost benefits from advanced technology application currently exist.

5. The most attractive areas for FEGS R&D, where interests differ from MEP needs, are those of natural gas burning systems for base self sufficiency, and adiabatic diesels for remote site applications. The major dynamic for such R&D is not technology driven, however, but depends on policy decisions regarding base self-sufficiency, and on civil sector researchs in electric energy generators.

6. This study did not comprehensively address renewable energy systems for facilities applications. However, two tentative conclusions are possible based upon the ATES data and designs: Stand alone, i.e. non-hybrid, non-grid connected photovoltaic systems do not appear attractive for general facilities applications. Wind turbines appear be generically attractive enough to warrant detailed consideration whenever site specific factors are encouraging.

7. If USAF institutes a base self sufficiency policy which includes a requirement or potential for power generation inside the fence, then advanced technologies have the potential to be operationally effective at a price which is competitive with utility electric costs. The scope and scale of investment and potential cost savings would almost certainly require a major R&D program.

8. There exist major deficiencies in integrated logistics support for facilities electric generating systems. The lack of standardization has had major impacts on training, spare parts availability, and readiness. Further research in this area would almost certainly result, if implemented, in enhanced cost and operational effectiveness.

GLOSSARY OF TERMS

AC	Actively Cooled Photovoltaic System
AD	Adiabatic Diesel Engine
AFCC	USAF Communications Command
AFSC	USAF Systems Command
AFWAL	Air Force Wright Aeronautical Laboratories
AGE	Aircraft Ground Equipment
AGS	Aircraft Generation Squadron
ALC	Air Logistics Center
AMS	Avionics Maintenance Squadron
ATC	USAF Air Training Command
ATES	Advanced Terrestrial Energy Study
CAMS	Consolidated Aircraft Maintenance Squadron
CASS	Centralized Aircraft Support System
CC	Closed Cycle Gas Turbine
CCT	Combat Control Team
CRS	Components Repair Squadron
DED	Diesel Engine Driven
EC	Photoelectrical Photovoltaic System
EMI	Electromagnetic Interference
EMS	Equipment Maintenance Squadron
ESC	USAF Engineering and Services Center
FACP	Forward Air Control Party
FEGS	Facilities Electric Generating System
FMS	Field Maintenance Squadron
FP	Free Piston Stirling Engine
GED	Gasoline Engine Driven
GTED	Gas Turbine Engine Driven
IR	Infra-red
KS	Kinematic Stirling Cycle Engines
LCC	Life Cycle Cost
MAC	USAF Military Airlift Command
MADM	Multiple Attribute Decision Model
MCDM	Multiple Criteria Decision Model
MEP(S)	Mobile Electric Power (System)
MMS	Munitions Maintenance Squadron
MTBF	Mean Time Between Failures
MTBO	Mean Time Between Overhauls
NCO	Non-Commissioned Officer
NR	Non-Regenerative Gas Turbines
OCONUS	Outside the Continental United States
OMS	Organizational Maintenance Squadron
PA	Phosphoric Acid Fuel Cell
PACAF	Pacific Air Forces
POC	Point of Contact
PV	Flat Plate Photovoltaic System
R&D	Research and Development

RO	Regenerative Open Cycle Gas Turbine
ROC	Required Operational Capability
SAC	USAF Strategic Air Command
SON	Statement of Need
SP	Solid Polymer Fuel Cells
TACP	Tactical Air Control Party
TACS	Tactical Air Control System
TC	Turbo-compounded Diesel Engine
TD	Turbo-charged Diesel Engine
USAFE	US Air Forces Europe
WT	Wind Turbine

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